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ERRATA

Vol. 16, p. 141, line 9: Read "A stream of air was passed through the bell-jars," etc.

Vol. 16, p. 156: Add to legend for Plate 1, "1 = 5 A, 2 = 7 A, 3 = 9 A, 4 = 11 A, 5 = 7 B."

EQUILIBRIUM STUDIES OF SODIUM CARBONATES AND BICARBONATES IN SOME IDAHO SOILS

RAY E. NEIDIG AND HARRY P. MAGNUSON[1]

Idaho Agricultural Experiment Station

Received for publication May 16, 1923

The question of the reclamation of many natural alkali soils and the prevention of soils already in cultivation from becoming "salted out" is one of paramount importance in all irrigated regions. The attempt to utilize land containing a considerable percentage of salts has led many investigators to study the relative toxicity of the various alkali salts toward numerous crops. At present the Idaho Agricultural Experiment Station is carrying on an extensive project dealing with the determination of the tolerance of various crops toward alkali under Idaho soil conditions. The earlier investigations on tolerance of crops for alkali were based on the assumption that the amount of alkali added to the soil was the criterion to be followed in judging tolerance. This view, however, has been greatly changed in latter years by the work of investigators who base their view on toxicity from the amount of salts recoverable in the soil extract rather than from the salts added.

The work of Headley, Curtis and Scofield (5) has shown that when sodium carbonate is added to a soil and allowed to remain in contact for several weeks that the total amount of recoverable salts, including both the normal carbonate and the bicarbonate, is much less than the quantity added. When two types of soils were studied, a sandy and a loam soil, they found that the amount of carbonate salts recoverable from the loam soil was very much less than that recoverable from the sandy soil, indicating a different amount of absorption[2] or retention of carbonates by soils of different chemical composition and physical structure. The great discrepancy between the amount of salts added and the amount of salts recoverable in the soil extract has led to conflicting statements in the literature on the relative toxicity of alkali salts when the toxicity is based on added salts rather than the recoverable salts.

Harris and Pittman (4), in their work with added alkali, mention the discrepancy between the amount of carbonate salts added to soils and the amount recoverable in a water extract, observing also that more injury resulted to plants when grown in sand than when grown in a loam soil, both receiving equal amounts of added sodium carbonate.

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[1] The data in this paper have been submitted in thesis form to the faculty of the University of Idaho by Harry P. Magnuson in partial fulfillment of the requirements for the degree of Master of Science in Agriculture.

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[2] The term absorption is used in this paper to refer to all cases of retention of salts by the soil whether the phenomena be primarily absorption or adsorption as distinguished by some writers, or a combination of both.

Kearney (7) of the United States Department of Agriculture, Bureau of Plant Industry, studied the relative absorption of soil by sodium carbonate and sodium chloride and found that when equal amounts of sodium chloride and sodium carbonate were added to sand the amount of sodium carbonate in the solution from the sand was much less than the sodium chloride, using the electrical resistance method as a basis of comparison. It is evident from past experiments, therefore, that the actual toxicity of salts must be based on the amount of salt present in solution, in other words, recoverable salt rather than added salt.

Another point of interest brought out by Headley, Curtis and Scofield in their work with soil is that when sodium carbonate is added to a soil a considerable amount of sodium bicarbonate is recovered. Some of the normal carbonate is thus changed to bicarbonate. They state that the comparative toxicity of sodium carbonate and sodium bicarbonate is approximately the same when the total of the carbonate salts recoverable is considered rather than the percentage of salts added to the soil. In other words the toxicity of these salts in the soil is directly associable with the quality of the basic radical in the salts recoverable.

Kearney and Cameron (8) have shown that the bicarbonate salt of sodium is less toxic in water solution to white lupine than sodium carbonate. It has also been shown by Cameron and Briggs (2) that in water solutions of sodium carbonate, sodium bicarbonate is gradually formed until approximately one-half of the sodium carbonate is changed over to the sodium bicarbonate. It is evident, therefore, that in all alkali studies where normal sodium carbonate was used and the results of toxicity were based on salts added, an error was introduced owing to the reversion of some of the normal sodium carbonate to the sodium bicarbonate as well as the fact that soils withhold much of the sodium carbonate from the water extract. All these facts make it obvious that the toxicity of alkali should be judged by the salts recoverable rather than the salts added to the soil.

In our investigations dealing with tolerance of crops for alkali, preliminary work indicated that the amount of alkali salts, especially sodium carbonate, that could be recovered in the water extract varied considerably with different soil types. It was thought of interest to determine for definite and widely different soil types as found in Idaho, the relative absorption or retention factor, if such it might be called, and also the amount of carbonate salts recoverable throughout stated intervals of time, i.e., this study concerned the equilibrium of the carbonate salts, sodium carbonate and sodium bicarbonate, as affected by these different soil types when in contact for a definite period of time under uniform moisture conditions.

It was also thought of practical importance to ascertain the effect of adding additional amounts of the carbonate salts to these soils after they had reached an apparent equilibrium as judged by the analyses of the soil extract and noting whether the soil would absorb or retain an additional amount of carbonate salts. The findings of this interesting phase of the investigation will be discussed later in the paper after the methods and data are introduced.

Preliminary studies with Idaho soils indicated that some of the soil types showed widely different physical and chemical properties. Various differences were also noted in their power of retaining carbonates when known amounts of carbonate salts were added to the soils. Three soils showing the widest differences in properties were selected for the experiment. They were, Palouse silt loam, Caldwell silt loam subsoil and Boise silt loam. The Boise silt loam consisted of two samples, one of which was comparatively free from natural alkali, while the other sample represented a soil containing considerable alkali salts consisting of chlorides and sulfates.

DESCRIPTION OF SOILS

The Palouse silt loam soil is a dark colored soil high in fertility and organic matter. When wet, this soil is black in color. The soil used in the experiment was taken from the first nine inches of surface soil on the Experiment Station plots at Moscow.

The Caldwell silt loam subsoil sample was taken at a depth of five feet in the Caldwell silt loam series. This subsoil is a grayish yellow, silty clay loam, and very compact. The sample was also taken from soil on the experimental farm.

The Boise silt loam samples were secured from southern Idaho near Parma and Caldwell. One sample containing considerable natural alkali salts of chlorides and sulfates, while the other contained very little alkali. The soil is a grayish colored light sandy loam and is soft and ashy to the touch, carrying a large amount of silt. The two Boise silt loam soils were secured from points approximately fifteen miles apart, and while they are both classified as Boise silt loam, they may differ slightly in their physical and chemical properties.

The four soils were examined for alkali salts and found to contain the following percentages expressed on the anhydrous basis.

SOIL TYPE	SODIUM CARBONATE	SODIUM BICARBONATE	SODIUM CHLORIDE	SODIUM SULFATE
	per cent	*per cent*	*per cent*	*per cent*
Palouse silt loam	0.000	0.018	0.004	0.006
Caldwell silt loam	0.000	0.018	0.000	0.004
Boise silt loam	0.000	0.018	0.712	0.119
Boise silt loam	0.000	0.041	0.002	0.000

PREPARATION OF THE SOILS

A series of eight 1-gallon jars was filled for each of the four soils. To four jars in each series were added different amounts of the normal sodium carbonate salts, namely, 0.25, 0.5 1.0 and 1.5 gm. per 100 gm. soil calculated on the anhydrous soil basis. To the remaining four jars of each series were added amounts of sodium bicarbonate equivalent in each case to the amounts of normal carbonate salts used in the first series. The actual weights of sodium bicarbonate used were 0.4, 0.8, 1.6 and 2.4 gm. per 100 gm. anhydrous soil. These salts were thoroughly mixed with the soils on December 23, 1920, and a sample taken on the same day and analyzed for recoverable carbonate and bicarbonate salts by the method described later in this publication.

An additional series of experiments was carried out which had for its object the determination of the equilibrium of the carbonate and bicarbonate salts in these same soils when kept in an air-dry condition during the same periods as the soils to which water was added. A small portion of the air-dried soils mixed on December 23, 1920, was set aside for this purpose. These were also analyzed at stated intervals on November, 2, 1921 and February 7, 1923. The entire period of contact was a little over two years. The results are given in table 5.

METHODS USED

The estimation of the carbonate salts in the water extract was made by the methods described by the Bureau of Soils (2) with the exception that in this work the proportion of water to soil was ten to one instead of twenty to one. Congo red indicator was used instead of methyl orange due to the fact that extracts of some of the soils were dark in color which masked the end point when methyl orange was used as an indicator. Samples were taken from each jar by means of a soil tube. In this manner several cores, representing the entire depth of soil, were secured from each jar. These cores were very carefully mixed and a

composite sample taken for analysis. The soils sampled on December 23, 1920, and January 3, 1921, were dried before analyzing, but in all other samples the moist soil was analyzed directly, since drying was found to slightly change the equilibrium.

The soils were kept at a moisture content of approximately 20 per cent throughout the first series of the experiment which was from December 23, 1920 to July 26, 1921. Four samples of each soil were taken during this period; the first sample, on December 23, 1920, the date of mixing; the second, on January 3, 1921; the third on February 25, 1921; and the last, on July 26, 1921. After this last date the soils were allowed to air-dry. The data for this first equilibrium period are given in table 1 and also in figures 1–4.

Table 1 contains all the data on the carbonate salts added to the soil and carbonate salts recovered in the water extract for all periods included in the first series for the four soils. The additions of sodium bicarbonate are the molecular equivalents of the corresponding additions of normal sodium carbonate. The salts added and recovered are expressed as grams per 100 grams of anhydrous soil. The column headed total sodium carbonate equivalent represents the sum of the normal carbonate recovery and the bicarbonate recovery, which is calculated to its equivalent of normal sodium carbonate. Water extracts of soils made after adding bicarbonate salts showed an alkaline reaction to phenolphthalein, indicating a reversion to normal carbonate and possibly a small amount hydrolyzed to the hydroxide. Either compound would appear alkaline to phenolphthalein. In all the data, however, the results on this particular portion of the water extract are calculated as normal sodium carbonate.

The results of the first series indicated that the soils had reached a point where only a slight reduction in total recovery of soluble carbonate salts was noted when examined. At this point it was thought of interest to study the effect of adding a large quantity of carbonate and bicarbonate salts to each of these soils to ascertain whether the soils had reached their maximum capacity of absorption of these salts.

Hence to the same soils used in the first experimental period and which were allowed to become air-dry, additional amounts of sodium carbonate and sodium bicarbonate were added on August 10, 1921. One gram of sodium carbonate per 100 gm. anhydrous soil was added to the sodium carbonate group and 1.6 gm. sodium bicarbonate, to the sodium bicarbonate group of soils. In the second period therefore, the soils contain the original amount of carbonate salts which were added, together with the additional 1 per cent of sodium carbonate or the equivalent in sodium bicarbonate. This second addition marks the beginning of the second series, the results of which are given in table 2. The soils were sampled September 15, 1921, December 12, 1921, June 10, 1922, and October 19, 1922. The time between the first two samplings, it should be noted was a little less than fourteen and one-half months. The soils were kept at approximately fifteen per cent moisture content throughout the entire second period. The results are given in table 2 and figures 1–4.

All the results expressed in this paper, the reader should bear in mind, are calculated from the acid radicals HCO_3 and CO_3 which were directly deter-

TABLE 1

Carbonates added and recovered from soils maintained at optimum moisture content. First series

POT NUMBER	SALTS ADDED PER 100 GM. ANHYDROUS SOIL		SALTS RECOVERED IN WATER EXTRACT PER 100 GRAMS OF ANHYDROUS SOIL											
			December 23, 1920			January, 3, 1921			February 25, 1921			July 26, 1921		
	Na_2CO_3	$NaHCO_3$	Na_2CO_3	$NaHCO_3$ expressed as Na_2CO_3	Total Na_2CO_3 equivalent	Na_2CO_3	$NaHCO_3$ expressed as Na_2CO_3	Total Na_2CO_3 equivalent	Na_2CO_3	$NaHCO_3$ expressed as Na_2CO_3	Total Na_2CO_3 equivalent	Na_2CO_3	$NaHCO_3$ expressed as Na_2CO_3	Total Na_2CO_3 equivalent
	gm.	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*
Palouse silt loam														
1	0.25		0.000	0.183	0.183	0.000	0.081	0.081	0.012	0.046	0.058	0.000	0.030	0.030
2	0.5		0.083	0.241	0.324	0.063	0.132	0.195	0.026	0.089	0.115	0.012	0.093	0.105
3	1.0		0.353	0.334	0.687	0.228	0.193	0.421	0.167	0.115	0.282	0.137	0.142	0.279
4	1.5		0.706	0.406	1.110	0.416	0.183	0.599	0.293	0.219	0.572	0.325	0.151	0.476
5		0.4	0.000	0.180	0.180	0.020	0.091	0.111	0.006	0.060	0.066	0.000	0.029	0.029
6		0.8	0.000	0.456	0.456	0.083	0.142	0.225	0.069	0.067	0.136	0.017	0.089	0.106
7		1.6	0.000	0.915	0.915	0.228	0.193	0.421	0.152	0.121	0.273	0.076	0.143	0.219
8		2.4	0.020	1.250	1.270	0.374	0.152	0.526	0.470	0.172	0.642	0.232	0.141	0.373
Caldwell silt loam subsoil														
9	0.25		0.062	0.153	0.215	0.062	0.091	0.153	0.074	0.052	0.126	0.048	0.041	0.089
10	0.5		0.187	0.122	0.309	0.162	0.091	0.257	0.146	0.047	0.193	0.123	0.032	0.155
11	1.0		0.644	0.122	0.766	0.374	0.040	0.414	0.288	0.079	0.367	0.207	0.059	0.266
12	1.5		0.852	0.132	0.984	0.644	0.010	0.654	0.385	0.079	0.464	0.292	0.048	0.340
13		0.4	0.000	0.213	0.213	0.083	0.071	0.154	0.072	0.062	0.134	0.048	0.046	0.094
14		0.8	0.042	0.427	0.469	0.166	0.071	0.237	0.184	0.054	0.238	0.111	0.048	0.159
15		1.6	0.104	0.862	0.906	0.395	0.010	0.405	0.313	0.067	0.380	0.260	0.069	0.329
16		2.4	0.124	1.180	1.304	0.770	0.050	0.820	0.551	0.133	0.684	0.548	0.067	0.615
Boise silt loam containing natural alkali, chlorides and sulfates														
17	0.25		0.041	0.101	0.142	0.020	0.071	0.091	0.024	0.046	0.070	0.010	0.033	0.043
18	0.5		0.124	0.091	0.215	0.083	0.081	0.164	0.051	0.043	0.094	0.049	0.053	0.102
19	1.0		0.623	0.000	0.623	0.270	0.101	0.371	0.270	0.029	0.299	0.152	0.047	0.199
20	1.5		0.873	0.061	0.934	0.624	0.010	0.634	0.536	0.103	0.639	0.358	0.099	0.457
21		0.4	0.000	0.233	0.233	0.020	0.071	0.091	0.060	0.026	0.086	0.005	0.033	0.038
22		0.8	0.000	0.456	0.456	0.062	0.091	0.153	0.073	0.029	0.102	0.057	0.038	0.095
23		1.6	0.020	0.781	0.801	0.250	0.091	0.341	0.207	0.081	0.288	0.165	0.062	0.227
24		2.4	0.083	1.078	1.161	0.520	0.010	0.530	0.535	0.015	0.550	0.345	0.123	0.468
Boise silt loam free from alkali chlorides and sulfates														
25	0.25		0.146	0.071	0.217	0.083	0.081	0.164	0.094	0.057	0.151	0.077	0.039	0.116
26	0.5		0.104	0.151	0.257	0.250	0.050	0.300	0.245	0.008	0.253	0.137	0.047	0.184
27	1.0		0.644	0.071	0.715	0.436	0.030	0.466	0.464	0.096	0.560	0.266	0.079	0.345
28	1.5		0.996	0.010	1.006	0.749	0.020	0.769	0.643	0.041	0.684	0.511	0.069	0.580
29		0.4	0.047	0.193	0.240	0.104	0.091	0.195	0.093	0.058	0.151	0.085	0.035	0.120
30		0.8	0.083	0.344	0.427	0.228	0.060	0.288	0.209	0.031	0.240	0.153	0.041	0.194
31		1.6	0.166	0.668	0.834	0.395	0.050	0.445	0.360	0.107	0.467	0.326	0.046	0.372
32		2.4	0.104	1.239	1.343	0.644	0.020	0.664	0.650	0.132	0.782	0.562	0.065	0.627

TABLE 2

Carbonates added and recovered from soils maintained at optimum moisture content. Second series

POT NUMBER	SALTS ADDED PER 100 GM. ANHYDROUS SOIL		SALTS RECOVERED IN WATER EXTRACT PER 100 GRAMS OF ANHYDROUS SOIL											
			September 15, 1921			December 12, 1921			June 10, 1922			October 19, 1922		
	Na_2CO_3	$NaHCO_3$	Na_2CO_3	$NaHCO_3$ expressed as Na_2CO_3	Total Na_2CO_3 equivalent	Na_2CO_3	$NaHCO_3$ expressed as Na_2CO_3	Total Na_2CO_3 equivalent	Na_2CO_3	$NaHCO_3$ expressed as Na_2CO_3	Total Na_2CO_3 equivalent	Na_2CO_3	$NaHCO_3$ expressed as Na_2CO_3	Total Na_2CO_3 equivalent
	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.
Palouse silt loam														
1	1.0		0.363	0.064	0.427	0.237	0.110	0.347	0.197	0.171	0.368	0.165	0.224	0.389
2	1.0		0.357	0.107	0.464	0.324	0.194	0.518	0.269	0.239	0.508	0.290	0.134	0.424
3	1.0		0.579	0.153	0.732	0.472	0.040	0.512	0.465	0.009	0.474	0.412	0.024	0.436
4	1.0		0.684	0.190	0.874	0.748	0.230	0.978	0.638	0.350	0.988	0.695	0.110	0.805
5		1.6	0.326	0.074	0.400	0.249	0.097	0.346	0.174	0.206	0.380	0.171	0.108	0.279
6		1.6	0.048	0.213	0.261	0.203	0.106	0.309	0.252	0.186	0.438	0.173	0.216	0.389
7		1.6				0.593	0.141	0.734	0.440	0.213	0.653	0.418	0.112	0.530
8		1.6				0.695	0.142	0.837	0.640	0.187	0.827	0.589	0.129	0.718
Caldwell silt loam subsoil														
9	1.0		0.495	0.117	0.612	0.487	0.079	0.566	0.368	0.023	0.391	0.345	0.019	0.364
10	1.0		0.470	0.105	0.575	0.714	0.068	0.782	0.498	0.038	0.536	0.512	0.000	0.512
11	1.0		0.700	0.064	0.764	0.666	0.000	0.666	0.462	0.060	0.522	0.448	0.000	0.448
12	1.0		0.841	0.081	0.922	0.690	0.044	0.734	0.471	0.056	0.527	0.408	0.014	0.422
13		1.6	0.353	0.108	0.461	0.256	0.071	0.327	0.323	0.047	0.370	0.311	0.020	0.331
14		1.6	0.681	0.098	0.779	0.481	0.064	0.545	0.432	0.184	0.616	0.335	0.019	0.354
15		1.6	0.876	0.163	1.039	0.885	0.077	0.962	0.860	0.000	0.860	0.790	0.015	0.805
16		1.6	1.455	0.165	1.620	1.214	0.055	1.269	1.045	0.032	1.077	1.002	0.059	1.061
Boise silt loam containing natural alkali, chlorides and sulfates														
17	1.0		0.491	0.042	0.533	0.496	0.063	0.559	0.324	0.032	0.356	0.235	0.069	0.304
18	1.0		0.510	0.115	0.625	0.485	0.082	0.567	0.371	0.067	0.438	0.374	0.000	0.374
19	1.0		0.841	0.021	0.861	0.734	0.081	0.815	0.628	0.000	0.628	0.650	0.039	0.689
20	1.0		1.322	0.000	1.322	1.030	0.081	1.111	0.842	0.000	0.842	0.835	0.093	0.928
21		1.6	0.463	0.077	0.540	0.294	0.063	0.357	0.276	0.050	0.326	0.228	0.058	0.286
22		1.6	0.624	0.108	0.732	0.456	0.130	0.586	0.400	0.005	0.405	0.330	0.051	0.381
23		1.6	0.924	0.225	1.149	0.814	0.104	0.918	0.674	0.000	0.674	0.621	0.098	0.719
24		1.6	1.121	0.071	1.192	1.000	0.013	1.013	0.824	0.000	0.824	0.836	0.048	0.884
Boise silt loam free from alkali chlorides and sulfates														
25	1.0		0.543	0.078	0.621	0.459	0.204	0.663	0.456	0.000	0.456	0.365	0.065	0.430
26	1.0		0.814	0.066	0.880	0.281	0.174	0.455	0.502	0.000	0.502	0.508	0.025	0.533
27	1.0		1.045	0.113	1.158	0.952	0.000	0.952	0.760	0.000	0.760	0.720	0.044	0.764
28	1.0		1.011	0.075	1.086	1.098	0.000	1.098	0.740	0.000	0.740	0.816	0.000	0.816
29		1.6	0.685	0.177	0.862	0.513	0.042	0.555	0.334	0.054	0.388	0.428	0.009	0.437
30		1.6	0.576	0.114	0.690	0.700	0.093	0.793	0.520	0.000	0.520	0.440	0.096	0.536
31		1.6	0.935	0.167	1.102	0.844	0.132	0.976	0.886	0.005	0.891	0.792	0.000	0.792
32		1.6	1.378	0.219	1.597	1.152	0.132	1.284	1.020	0.000	1.020	1.062	0.019	1.081

mined in the water extract as such. They are arbitrarily calculated to sodium carbonate in order to compare them with the percentages of sodium salts added.

Table 3 contains data corresponding in detail in tables 1 and 2 with the exception that the results are all expressed on the basis of percentage of recovery of the salts calculated from amount of salts added for all concentrations of each soil.

Table 4 represents the equilibrium that is established at the different periods between the sodium carbonate and sodium bicarbonate salts. The data are obtained by calculating the carbonate fraction of the recovery to per cent of total recovery.

Table 5 represents the data for the recovery from that portion of the first series which was taken out at the initial mixing and kept in the air-dry condition throughout the period of the first series. It corresponds in detail to table 1.

EXPLANATION OF THE CHARTS

In order to bring out more clearly the results given in tables 1 and 2 for the four soils, charts were prepared which illustrate graphically the data.

Figures 1–4 include all the data given in tables 1 and 2. The reader must bear in mind that in all cases the sodium bicarbonate curve is expressed in terms of the equivalent of sodium carbonate. As an explanation it may be said that the numerical ratio of sodium carbonate to sodium bicarbonate is 0.63 to 1.0. The figures include curves showing the per cent of each salt recovered after definite periods of contact as indicated by the chart. The total salt recovery is also illustrated by a curve. This curve is the sum of the sodium carbonate recovered together with the sodium bicarbonate. The sodium bicarbonate is, however, calculated to the equivalent of sodium carbonate. The break in the curve, between the dates July 26 and August 10, represents the time of preparation of the soils and the extra addition of salts for the second series. These soils were allowed to stand for an additional short period before sampling in order to establish partial equilibrium. The first sampling of the second series was made on September 15, 1921.

Figures 5 and 6 show the amounts of salts added in both series 1 and 2 for all soils; the amount of each salt recovered at the final period of analysis; and lastly the total salt recovery for each soil. These figures show by means of graphs the final results of the entire time of contact and may well be called summary of graphs which represent the total salt recovery for each individual soil for the entire period of the experiment.

DISCUSSION

In discussing tables 1–4 the period from December 23, 1920 to July 26, 1921 will be referred to as the first series; from August 10, 1921 to October 19, 1922 as the second series. The first four numbers for each soil will be referred to as the carbonate group or additions, and the last four as the bicarbonate. The

TABLE 3

Ratio of salts recovered to salts added in terms of carbonate

POT NUMBER	FIRST SERIES						SECOND SERIES			
	Portion maintained at optimum moisture content				Portion left air dry		Maintained at optimum moisture content			
	Dec. 23, 1920	Jan. 3, 1921	Feb. 25, 1921	July 26, 1921	Nov. 2, 1921	Feb. 7, 1923	Sept. 15, 1921	Dec. 12, 1921	June 10, 1922	Oct. 19, 1922
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
					Palouse silt loam					
1	73	32	23	12	56	52	33	27	29	32
2	66	39	23	21	56	56	31	34	34	28
3	68	42	28	28	61	58	36	25	23	22
4	74	40	38	32	66	62	35	39	40	32
5	74	44	26	12	78	76	32	27	30	22
6	91	45	27	21	82	81	17	21	29	26
7	91	42	27	21	82	80		36	32	26
8	85	35	42	25	80	79		33	33	28
					Caldwell silt loam subsoil					
9	86	61	50	35			49	45	31	29
10	61	51	38	31	47	47	38	52	35	34
11	76	41	36	26			38	33	26	22
12	65	44	31	23	55	55	36	29	21	17
13	85	61	53	37	63	61	37	26	29	26
14	94	47	47	31	71	67	52	36	41	23
15	90	40	38	32	61	57	51	48	43	40
16	86	55	45	41	73	73	64	51	43	42
					Boise silt loam containing natural alkali chlorides and sulfates					
17	56	35	28	17	55	67	42	44	28	24
18	43	32	18	20	37	47	41	38	29	25
19	62	37	29	19	45	43	43	40	31	34
20	62	42	42	30	51	48	52	44	33	37
21	93	36	34	15	58	66	43	28	26	22
22	91	30	20	19	68	56	49	39	27	25
23	80	34	28	22	61	53	57	46	33	36
24	78	35	36	31	63	36	47	40	33	35
					Boise silt loam free from alkali chlorides and sulfates					
25	86	65	60	46	65	48	50	53	36	34
26	51	60	50	36	62	43	59	30	33	35
27	71	46	56	34	54	55	58	47	38	38
28	66	50	46	38	56	57	43	44	29	32
29	96	78	60	48	73	66	69	44	31	35
30	85	57	48	39	75	71	46	53	34	35
31	83	44	46	37	73	65	55	49	44	37
32	82	44	52	41	71	68	63	51	40	43

TABLE 4

Ratio of normal carbonate to total carbonate equivalent in recovery

POT NUMBER	FIRST SERIES						SECOND SERIES			
	Portion kept at optimum moisture				Air-dry portion					
	Dec. 23, 1920	Jan. 3, 1921	Feb. 25, 1921	July 26, 1921	Nov. 2, 1921	Feb. 7, 1923	Sept. 15, 1921	Dec. 12, 1921	June 10, 1922	Oct. 19, 1922
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
					Palouse silt loam					
1			21.7				85.0	68.5	53.3	42.2
2	25.6	32.6	22.6	11.5	7.5	15.4	77.0	62.4	53.0	68.7
3	51.4	54.0	59.2	49.2	28.2	39.5	79.2	92.2	98.0	94.6
4	63.6	69.5	51.1	68.2	46.8	56.5	78.3	76.2	64.6	86.4
5		18.0	9.1				81.5	71.8	45.7	61.4
6		36.8	50.6	16.1			18.4	65.8	58.0	44.5
7		54.2	55.6	34.7				80.8	67.1	78.9
8	1.5	71.1	73.2	62.3		2.0		83.1	77.2	82.0
					Caldwell silt loam subsoil					
9	28.8	40.2	58.8	54.0			81.0	86.0	94.3	94.8
10	60.6	63.4	75.6	79.4	57.0	48.8	82.0	91.4	93.0	100.0
11	84.0	90.3	78.5	77.8			92.0	100.0	88.2	100.0
12	86.6	98.0	83.0	86.0	73.0	72.0	91.4	94.1	89.4	96.7
13		53.8	53.6	51.2	3.4		76.6	78.4	87.5	94.0
14	8.9	70.0	77.3	69.7	9.2	4.1	87.5	88.4	70.8	94.5
15	11.4	97.5	82.5	79.1	14.2	2.1	84.2	92.0	100.0	98.0
16	10.3	94.0	80.6	89.2	3.4	7.0	89.4	95.5	97.0	94.5
					Boise silt loam containing natural alkali chlorides and sulfates					
17	28.8	22.2	34.3	23.2	39.0	39.5	92.0	88.8	91.0	77.2
18	57.6	50.6	54.2	48.0	50.0	50.0	81.7	85.5	84.5	100.0
19	100.0	72.8	90.5	76.4	67.1	67.0	97.7	90.0	100.0	94.6
20	92.8	98.5	84.0	78.3	76.8	72.0	100.0	92.6	100.0	90.0
21		22.0	70.0	13.1		8.5	85.7	82.4	85.0	80.0
22		40.5	71.5	60.0		3.1	85.3	78.0	98.0	86.5
23	2.5	73.3	72.4	72.8	2.6	6.4	80.5	88.6	100.0	86.6
24	7.1	98.0	97.4	74.4	1.7	44.2	94.2	98.6	100.0	94.0
					Boise silt loam free from alkali chlorides and sulfates					
25	67.3	50.6	62.2	66.4	56.8	56.0	87.8	69.2	100.0	85.0
26	40.5	83.4	97.0	74.6	62.2	73.5	92.3	61.8	100.0	94.3
27	90.0	93.5	83.0	77.0	78.2	70.0	90.1	100.0	100.0	94.0
28	99.0	97.5	94.0	88.1	71.1	73.4	93.3	100.0	100.0	100.0
29	19.6	53.3	61.5	70.7	17.9	14.5	79.4	90.5	86.2	98.0
30	19.4	79.2	87.2	78.8	12.9	9.5	83.5	88.4	100.0	82.2
31	19.9	88.8	77.2	87.7	10.3	13.1	84.6	86.4	99.5	100.0
32	8.4	97.0	83.2	89.6	5.6	10.6	86.4	90.0	100.0	98.4

additions and recoveries are expressed as grams per hundred grams of anhydrous soil. In inspecting the data in the tables the reader is urged to consider the general trend of results rather than the individual differences between recoveries of the salts that may appear from time to time. The difficulties encountered in obtaining thorough distribution of added salts as well as uniform samples of alkali soils is well known to all who have had experience in alkali investigations.

Palouse silt loam

A critical review of the data dealing with the Palouse silt loam soil shows the large amount of salts that are retained in the soil even when analyzed immediately after mixing the dry salts with the air-dry soil. The percentage of recovery in a water extract of this soil is slightly higher with the bicarbonate than the carbonate salts. It is to be noted that the actual amount of salts recovered with the various concentrations are, within relatively narrow limits proportionate to the amount of salts added.

The rapid change of carbonate salts to bicarbonate is shown by the fact that in the determination made immediately after mixing the salts and soil, considerable of the sodium carbonate is found changed to the bicarbonate. This is contrary to the action of the sodium bicarbonate additions at this time, for only in the heaviest addition of sodium bicarbonate is the normal carbonate found and in this case the amount is insignificant.

The second determination was made on January 3, 1921, or ten days after the salts had been mixed with the soil. During this period they had been kept in a moist condition. At this time the amount of salt retained by the soil had greatly increased, in fact it was practically twice the amount held by the soil when the first sample was taken. In the carbonate additions the carbonate recoveries for two of the concentrations were slightly greater at this period than the recoveries secured immediately after mixing the salts and air dry soil. It was observed that the smallest concentration of sodium carbonate (0.25 gm.) did not yield any recoverable salts as carbonate but had evidently changed into the bicarbonate since some bicarbonate was found in the water extract. This is also true for the first sampling.

In the bicarbonate additions a noticeable change has taken place in the equilibrium of the bicarbonates and carbonates in the soil for there is a large amount of bicarbonate salts changed into carbonates and are recovered as such in the soil extract, the proportion in fact being greater than the actual amounts of carbonate salts recovered from the corresponding carbonate additions.

On February 25, the total recovery of salts continues to fall in all cases except treatment number 8. There are slight rearrangements of the equilibrium of the salts in both additions at this period.

The final determination in this series made July 26, 1921 shows a continued decrease in total recovery in every case. This decrease, however, is very small as compared with the first two periods, the curve being almost a straight line

as shown in figure 1. It is evident that the decrease is greater in the lower concentrations resulting in a smaller recovery of the salts in the lower additions. This soil shows the power of retaining a smaller percentage of the higher than the lower additions of salts. This does not mean that the actual amount of salts retained by the soils receiving the largest additions is less than with the smaller additions. On the contrary, almost five times as much salt is retained by the soil with the greatest addition.

In this series, the per cent of the recovered salts appearing as normal carbonates generally increases with the amount of salts added throughout the series. However, this increase is not in the same ratio is that of the salts added.

The second series, table 2, shows the effect of adding an additional one per cent of sodium carbonate to the sodium carbonate series and an equivalent amount of sodium bicarbonate to the bicarbonate series. The additions were made on August 10, 1921, and moisture was added to the soil at this time. It must be remembered that the total additions of salts to this soil now are 1.25, 1.5; 2.0 and 2.5 gm. of carbonate per 100 gm. of anhydrous soil and their equivalents of sodium bicarbonate. In comparing subsequent recoveries, however, it is justifiable to consider the sum of the amount recovered on July 26, and that added on August 10, as the initial recoverable salt content for the second series. Considering this amount of salt as the basis for recovery we find a large decrease in recovery at the time of the first determination, which was made on September 15, 1921. It is also evident that the ratio of normal carbonate to the total recovery has become more uniform for all additions in both carbonate and bicarbonate groups.

In the second series, an inspection of table 2 and figure 1 shows that equilibrium has practically been established in the Palouse soil for all added concentrations at the time of the first sampling. This is only thirty-five days after the second additions were made to the soil. The last sampling, made over a year later than the initial one, shows only a very slight downward trend. The intermediate determinations show slight fluctuations, some indicating more recovery of salts than others. This is distinctly seen when the graphs in figure 1 are examined. Not much stress can be laid on these fluctuations for it may be due for the most part to differences in sampling these soils. It should be stated here that all concentrations of alkali used on the Palouse soil, especially in the second series resulted in a highly deflocculated soil. The soil was extremely sticky and showed all the appearances of a poor physical condition which is typical with an excess of black alkali.

It is to be observed that in all the highest additions of salts there is a proportionately higher percentage recovery than in the lowest additions. This in turn means that there is proportionately less retention of salts in the highest additions. But it must not be overlooked when commenting on these two facts, that the soil seems to possess a cumulative action in absorbing or retaining the salts. Taking the lowest addition, 0.25 gm., and comparing it with the highest addition, 1.5 gm., only 12 per cent is recovered in the first series

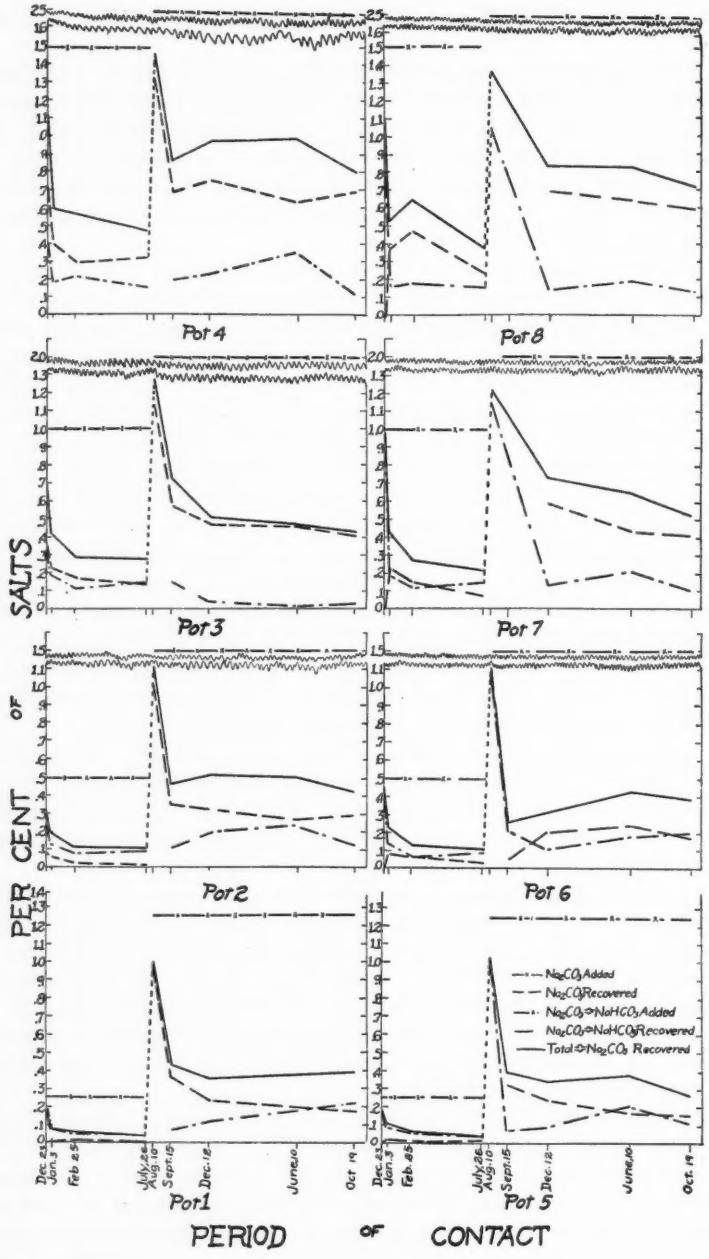

FIG. 1. CURVES REPRESENTING SODIUM CARBONATE AND SODIUM BICARBONATE ADDED TO AND RECOVERED FROM PALOUSE SILT LOAM, WHEN KEPT AT A MOISTURE CONTENT OF 15 TO 20 PER CENT

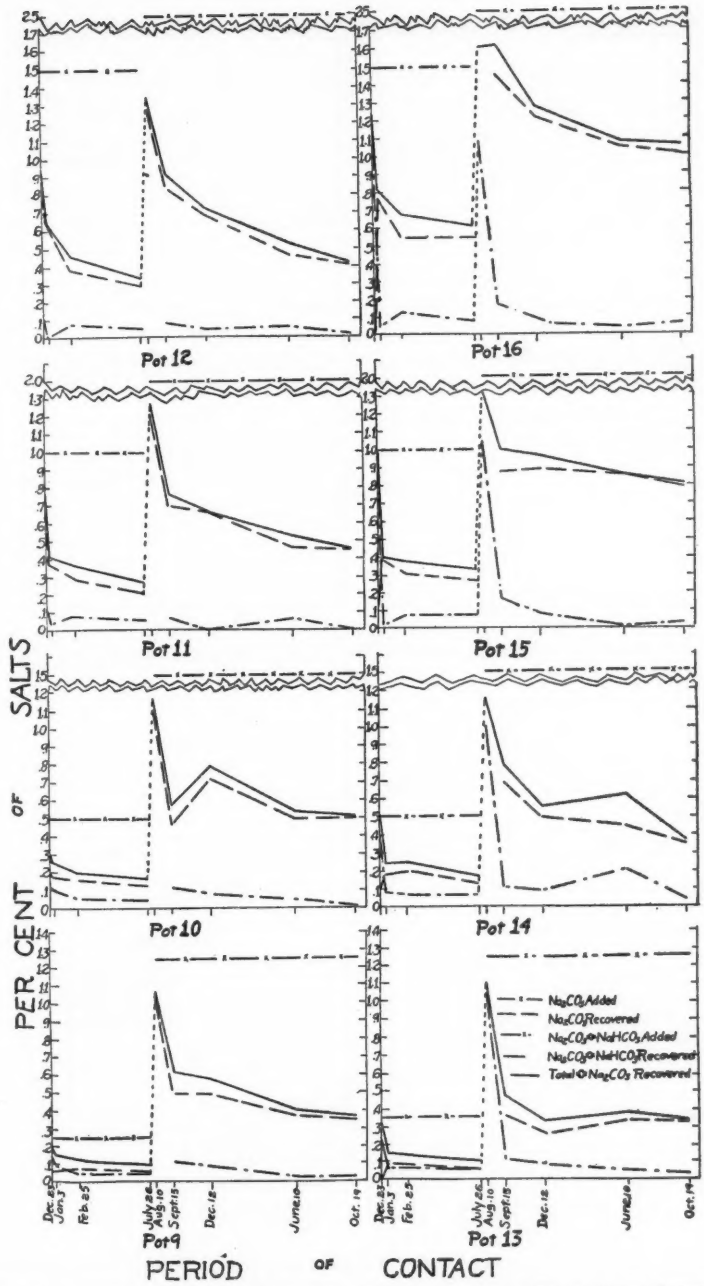

FIG. 2. CURVES REPRESENTING SODIUM CARBONATE AND SODIUM BICARBONATE ADDED TO AND RECOVERED FROM CALDWELL SILT LOAM SUBSOIL, WHEN KEPT AT A MOISTURE CONTENT OF 15 TO 20 PER CENT

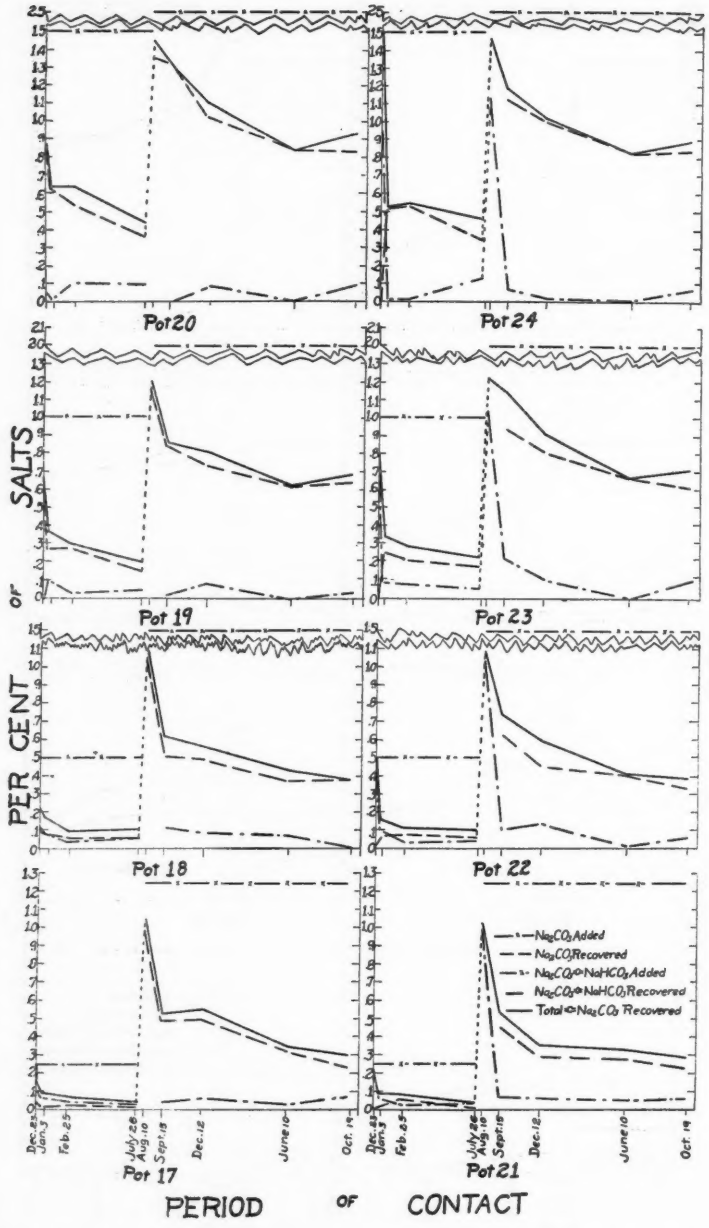

FIG. 3. CURVES REPRESENTING SODIUM CARBONATE AND SODIUM BICARBONATE ADDED TO AND RECOVERED FROM BOISE SILT LOAM CONTAINING NATURAL ALKALI CHLORIDES AND SULFATES, WHEN KEPT AT A MOISTURE CONTENT OF 15 TO 20 PER CENT

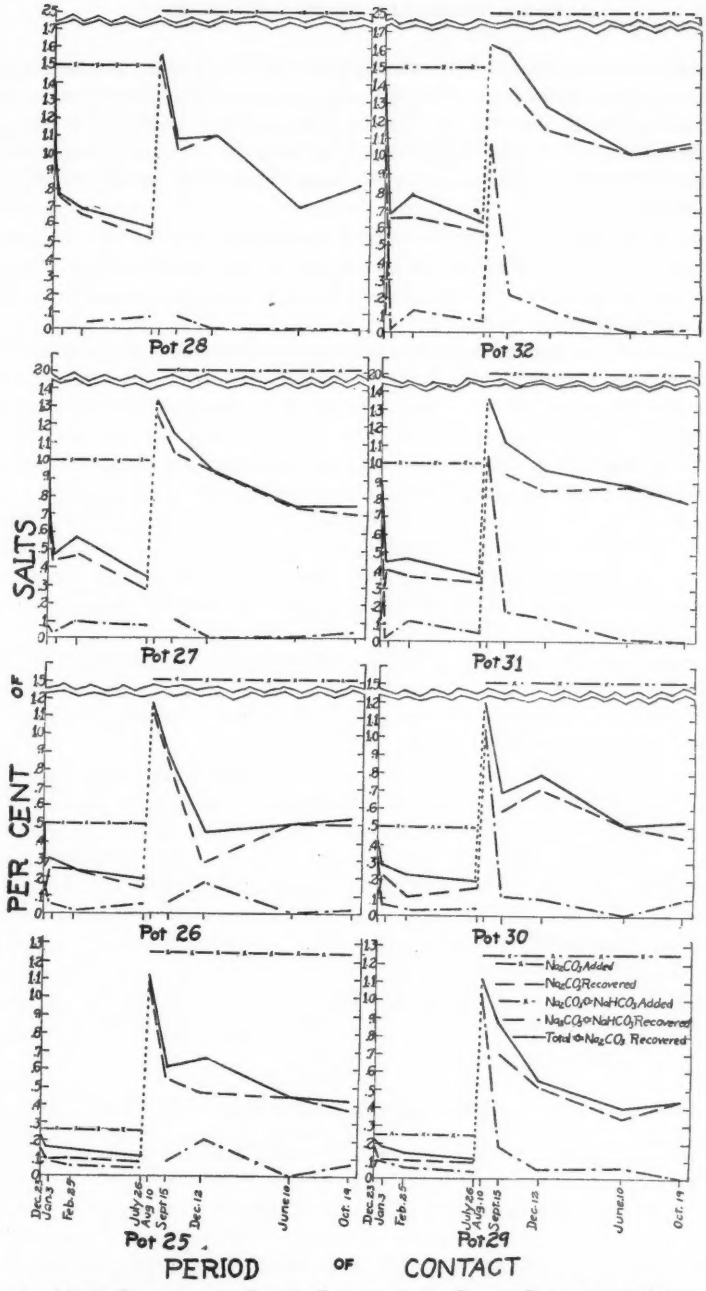

FIG. 4. CURVES REPRESENTING SODIUM CARBONATE AND SODIUM BICARBONATE ADDED TO AND RECOVERED FROM BOISE SILT LOAM FREE FROM ALKALI CHLORIDES AND SULFATES, WHEN KEPT AT A MOISTURE CONTENT OF 15 TO 20 PER CENT

from the lowest addition. With the highest addition 32 per cent is recovered. The percentage absorption is less with the highest addition but when actual amounts are considered we see that the amount of salts retained by the soil in the highest addition is much greater than with the lowest addition. With greater applications, this soil shows the power of increased actual retention or absorption.

In the second series the percentage of retention for the highest and lowest addition is equal at the end of the period, viz., 68 per cent for each treatment, while the actual amount of retention is 1.7 and 0.86 gm., respectively per 100 gm. of anhydrous soil.

It is noted that throughout this series we find a large recovery of normal carbonate in all concentrations. This is in accord with our earlier findings that a larger proportion of the normal carbonate is recovered in the heavier additions.

It is observed that this soil has the power of producing a certain amount of bicarbonate which is not increased with larger additions of salts. In the lowest additions of normal carbonate, it is all changed to bicarbonate. With higher additions the amount found does not exceed a definite level for both series. In the small additions, however, the level rises at once in the second series to the same level as the hither additions and remains there throughout the period.

In the bicarbonate series, we find the salt recovered primarily as such until the amount present exceeds the level found in the carbonate series. All higher additions which come above this general level are changed to normal carbonate. Figure 1 clearly illustrates this point.

In a study of table 3 we note that for the first determination December 23, 1920, all percentage recoveries are high but fairly uniform for all additions. As time goes on, there appears a divergence in percentage recovery between the lower and higher additions. The highest addition in the carbonate series gives a recovery two and one-half times that of the lowest, and in the bicarbonnate additions the final recovery is twice as great for the highest additions.

In the second series there are marked irregularities in the per cent recovered. At the end of the period there is, however, a uniformly higher recovery than is found at the end of the first series. This difference is greatest in the lower concentration, the final recovery in the higher concentrations in the second series being surprisingly near that of the first.

The Caldwell silt loam subsoil

Since a detailed discussion has been given for the Palouse silt loam soil it will not be repeated here but only the characteristic differences will be discussed for each of the three remaining soils. The Caldwell soil shows quite a similar recovery to the Palouse soil of both salts in the first analysis of the first series. The remaining three samplings of this series show a much higher recovery than in the Palouse soil.

In the normal carbonate additions of the first series the percentage of recovered salts is smaller for the larger than the smaller additions. This is true for both first and second series and is the reverse of the condition found on the Palouse soil. The bicarbonate additions to the Caldwell soil show the same type of recovery curve as the Palouse soil, differing only in that the Caldwell soil gives higher percentage recoveries in both series. The total carbonate recovery from the normal carbonate additions is lower throughout than that from the corresponding additions of the bicarbonate group.

From table 4 we see that the Caldwell soil shows little power of changing added carbonate salts to bicarbonate since practically all of the recovered salt from the carbonate additions is in the form of normal carbonate. On the other hand it does show marked activity in changing the bicarbonate additions to normal carbonate for by far the greater per cent of the added bicarbonate salt is recovered as the normal carbonate. The final percentage recoveries for both the normal carbonate and bicarbonate are very similar, ranging from 94 per cent to 100 per cent recovery as normal carbonate regardless of the salts added.

Boise silt loam

The Boise silt loam soil containing natural alkali salts, in the form of chlorides and sulfates, shows a lower initial recovery in the carbonate group than either the Palouse or Caldwell silt loam soils. The bicarbonate group, however, gives very nearly the same recovery as that of the Palouse soil. In the second and following determinations in the first series the relative recoveries are very nearly the same as those of the Palouse soil. The carbonate fraction of the total is very nearly the same as that for the Caldwell soils. The recoveries in the second series are high in the first determination, being almost equal to the results found in the Caldwell soil. The final recovery has dropped to the level of the Palouse soil.

In the alkali-free sample of the Boise silt loam we find the total recovery in the first determination about the same as the first two described soils, but in the succeeding determinations there is a smaller decrease in recovery than in any other soil giving us a larger recovery at the end of the first period than any other soil used in the experiment. In the second series the recovery is the largest throughout the period. This soil shows the weakest retentive power of any of the soils studied. It will be noted in the final determination of the second series that the percentage of recovery is less than the final recovery in the first series even though 1 gm. additional salt was added. The proportion of normal carbonate present in the first determination in the first series is the highest of all. This is especially noticeable in the bicarbonate group.

CARBONATE EQUILIBRIUM IN THE SOILS KEPT AIR-DRY

At the beginning of the experiment when the soils were mixed with the salts in an air-dry condition a portion of the soil containing each of the salt

TABLE 5

Carbonates added and recovered from soils maintained in an air-dry condition. First series

POT NUMBER	SALTS ADDED PER 100 GM. ANHYDROUS SOIL		SALTS RECOVERED IN WATER EXTRACT PER 100 GRAMS OF ANHYDROUS SOIL								
			December 23, 1920			November 2, 1921			February 7, 1923		
	Na_2CO_3	$NaHCO_3$	Na_2CO_3	$NaHCO_3$ expressed as Na_2CO_3	Total Na_2CO_3 equivalent	Na_2CO_3	$NaHCO_3$ expressed as Na_2CO_3	Total Na_2CO_3 equivalent	Na_2CO_3	$NaHCO_3$ expressed as Na_2CO_3	Total Na_2CO_3 equivalent
	gm.	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*
Palouse silt loam											
1	0.25		0.000	0.183	0.183	0.000	0.140	0.140	0.000	0.132	0.132
2	0.5		0.083	0.241	0.324	0.021	0.266	0.288	0.043	0.236	0.279
3	1.0		0.353	0.334	0.687	0.174	0.442	0.616	0.230	0.351	0.581
4	1.5		0.706	0.406	1.110	0.468	0.532	1.000	0.523	0.398	0.921
5		0.4	0.000	0.180	0.180	0.000	0.197	0.197	0.000	0.190	0.190
6		0.8	0.000	0.456	0.456	0.000	0.414	0.414	0.000	0.405	0.405
7		1.6	0.000	0.915	0.915	0.000	0.820	0.820	0.000	0.801	0.801
8		2.4	0.02	1.250	1.270	0.000	1.200	1.200	0.024	1.172	1.196
Caldwell silt loam subsoil											
9	0.25		0.062	0.153	0.215	*					
10	0.5		0.187	0.122	0.309	0.136	0.102	0.239	0.115	0.121	0.236
11	1.0		0.644	0.122	0.766	*					
12	1.5		0.852	0.132	0.984	0.610	0.226	0.936	0.592	0.232	0.824
13		0.4	0.000	0.213	0.213	0.005	0.153	0.158	0.000	0.153	0.153
14		0.8	0.042	0.427	0.469	0.032	0.322	0.355	0.014	0.324	0.338
15		1.6	0.104	1.065	1.169	0.087	0.523	0.610	0.120	0.458	0.578
16		2.4	0.124	1.180	1.304	0.038	1.160	1.100	0.077	1.021	1.098
Boise silt loam containing natural alkali, chlorides and sulfates											
17	0.25		0.041	0.101	0.142	0.054	0.083	0.138	0.067	0.102	0.169
18	0.5		0.124	0.091	0.215	0.092	0.093	0.186	0.120	0.118	0.238
19	1.0		0.623	0.000	0.623	0.305	0.149	0.454	0.288	0.142	0.430
20	1.5		0.873	0.061	0.934	0.392	0.178	0.770	0.521	0.204	0.725
21		0.4	0.000	0.233	0.233	0.000	0.146	0.146	0.014	0.151	0.165
22		0.8	0.000	0.456	0.456	0.000	0.341	0.341	0.009	0.276	0.285
23		1.6	0.02	0.781	0.807	0.016	0.595	0.611	0.034	0.500	0.534
24		2.4	0.083	1.078	1.161	0.016	0.940	0.956	0.240	0.302	0.542
Boise silt loam free from alkali chlorides and sulfates											
25	0.25		0.146	0.071	0.214	0.092	0.070	0.163	0.067	0.053	0.120
26	0.5		0.104	0.151	0.257	0.195	0.118	0.313	0.158	0.061	0.219
27	1.0		0.644	0.071	0.715	0.429	0.120	0.549	0.389	0.167	0.556
28	1.5		0.996	0.010	1.006	0.598	0.241	0.839	0.628	0.228	0.856
29		0.4	0.047	0.193	0.240	0.032	0.149	0.182	0.024	0.141	0.165
30		0.8	0.083	0.344	0.427	0.049	0.330	0.379	0.034	0.325	0.359
31		1.6	0.166	0.666	0.834	0.076	0.662	0.738	0.086	0.572	0.658
32		2.4	0.104	1.135	1.239	0.060	1.020	1.080	0.101	0.927	1.028

* Lost.

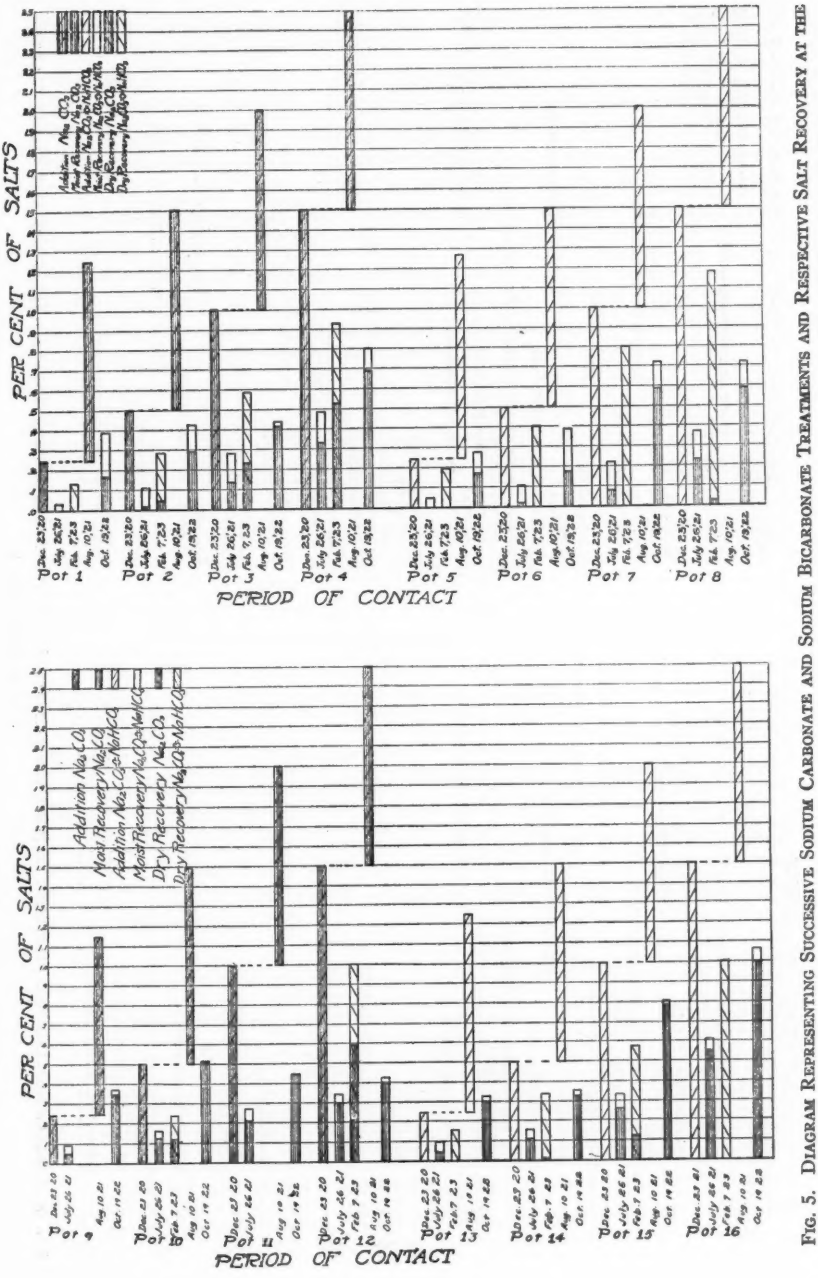

FIG. 5. DIAGRAM REPRESENTING SUCCESSIVE SODIUM CARBONATE AND SODIUM BICARBONATE TREATMENTS AND RESPECTIVE SALT RECOVERY AT THE END OF EACH SERIES

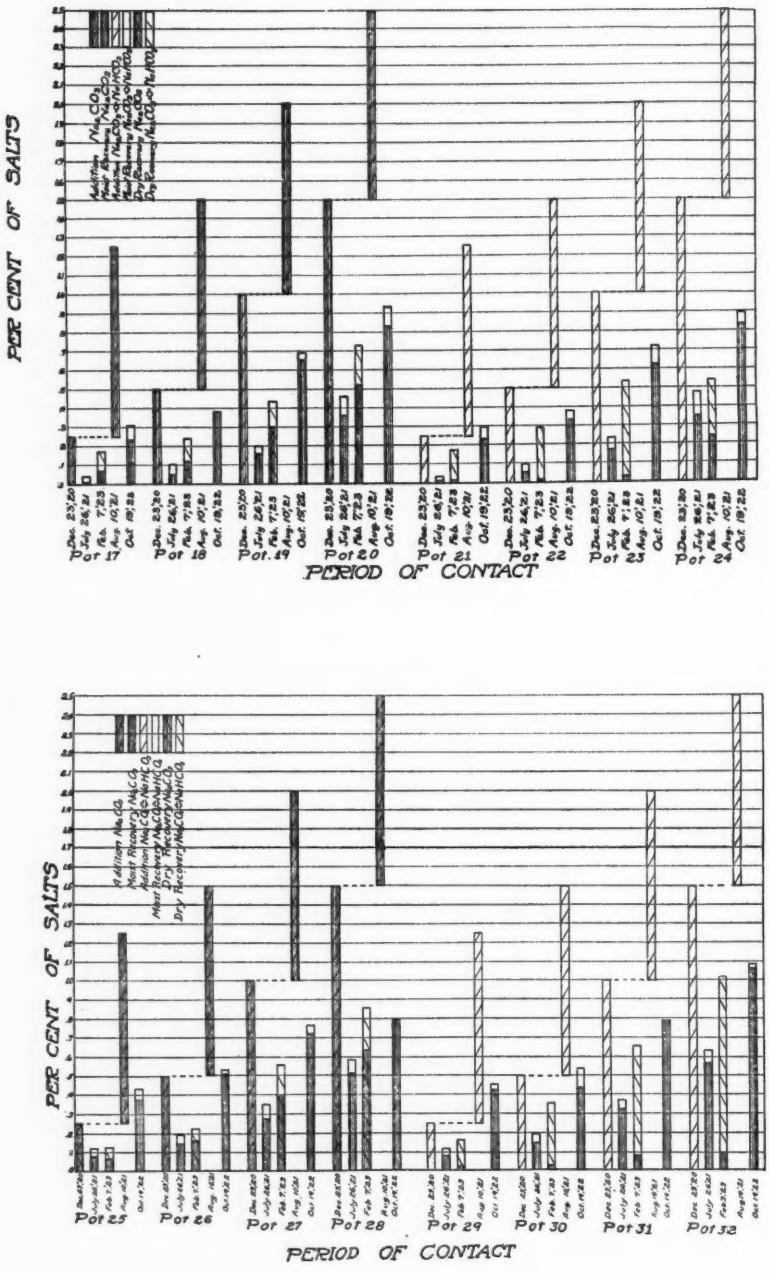

FIG. 6. DIAGRAM REPRESENTING SUCCESSIVE SODIUM CARBONATE AND SODIUM BICARBONATE TREATMENTS AND RESPECTIVE SALT RECOVERY AT THE END OF EACH SERIES

concentrations was placed in small wide-mouth bottles and set aside in the greenhouse. These soils were kept in an air-dry condition throughout the entire period of the experiment in order to observe the behavior of the carbonate and bicarbonate salts in air dry soils. The soil was analyzed December 23, 1920, immediately after mixing. The results are the same as given for the moist soils for that date. Additional determinations were made on November 2, 1921, approximately eleven months after mixing, and on February 7, 1923, approximately twenty-six months after the beginning of the experiment. The results are given in tables 3, 4 and 5.

While a comparison of the recoveries made eleven and twenty-six months after mixing shows variation in amounts recovered, a general similarity exists for all four soils in that the determinations made eleven months after mixing are considerably lower than the results obtained at the beginning of the experiment. The recoveries obtained twenty-six months after beginning the experiment, or fourteen months after the second sampling, show that very slight changes have resulted, and only a slight reduction in total recovery is noted.

In pots 24 and 26 there is noted a larger decrease in the amount of recoverable salt at the last period of sampling. These discrepancies are due to the fact that water leaked into these bottles from the greenhouse roof and the soils became moist before it was noticed. They were allowed to dry out again, but a change had taken place in the equilibrium as noted in the results.

In the dry condition, it was noticed that the soil did not change the bicarbonate salts into carbonates but the soils showed the same relative power to change carbonates into bicarbonates that was observed with these same soils when maintained in a moist condition. In pot 24 the high recovery of normal carbonate from the bicarbonate addition was due to the accidental contamination by water as previously mentioned.

In all soils the total recoveries of the bicarbonate additions are greater than the normal carbonate.

In the Boise silt loam containing natural alkali we find a higher percentage of recovery with the smallest addition than with the largest additions, both with the carbonate and bicarbonate. This is contrary to the results obtained on the other three soils.

THE ABSORPTION PHENOMENA OF SODIUM CARBONATE IN SOILS

It has long been known that some of the additions of sodium carbonate salts could not be recovered in a water extract of the soils. In other words, each soil has a capacity for retaining a certain portion of the added salt. The amount of sodium carbonate recoverable is an individual characteristic for each soil. Clays and soils high in organic matter are known to absorb more carbonate salts than sands.

The additions of carbonate produce a distinct physical and chemical effect on soils. In small amounts sodium carbonate has proved a stimulant to the growth of certain crops on many soils. In the alkali tolerance studies carried

on at this station the writers have repeatedly found stimulation as shown by increased yields of crops treated with small dilutions of sodium carbonate over the pots receiving no treatments. Other investigators have reported similar experiences.

In the present investigation it will be noted that four treatments were made to the first series, varying in concentration from 0.25 to 1.5 per cent sodium carbonate. It was found that the percentage of retention or absorption varied with the minimum and maximum additions of carbonates, for the soils in the experiment, some of the soils showing a smaller percentage retention with the minimum than with the maximum additions, and vice versa. This is only to be expected for it demonstrates the individual characteristic of each soil towards absorption. It must be borne in mind that the larger additions all show a much greater absorption in the soil, regardless of the percentage of recovery. When one per cent additional sodium carbonate was added to the soils in the second series, we had concentrations of 1.25 per cent as the minimum and 2.5 per cent as the maximum. These concentrations were sufficient to materially change the physical condition of the soil. It must be admitted that these concentrations of the second series are all far in excess of sodium carbonate which can be tolerated by crops. In considering the recovery of salts from these soils, we find that the addition of the one per cent sodium carbonate to soils in the first series had reached an equilibrium as indicated by chemical analysis of the water extract and to which the maximum addition of 1.5 per cent sodium carbonate was thought to show the maximum absorption showed instead an added capacity of absorbing sodium carbonate. One of the soils, e.g. the Palouse silt loam, attained almost a similar equilibrium at the first sampling as was found thirteen months later. The remaining soils all showed a decided decrease in salts recovered and a corresponding increase in salts absorbed.

It may seem somewhat strange that soils show an added capacity for absorption or retention of carbonate salts after the first equilibrium had taken place in the first series. A tentative explanation is offered here.

As early as 1888 Van Bemmelen (15) in studies on soil absorption concluded that the chief absorptive power of a soil is due to the colloidal oxides and silicates present in it. He stated that the soil contains colloids, colloidal silicates, iron oxide, silicic acid and humus substances, all of which bring about these reactions and tend to change the equilibrium, thereby causing considerable absorption in soils.

It is noted in this work that more carbonates are absorbed from concentrated than from dilute solutions. Even if the concentrations were very low, e. g. 0.25 per cent, the entire salt was not removed by the soil. This fact has been mentioned frequently in the literature in discussing absorption of salts by soils.

It is quite possible that sodium carbonate when added to soils reacts with the constituents already present in the soil and is therefore, removed from the

soil solution as carbonates or changed into other forms. One such possible reaction is that between sodium carbonate and the silicates of the soil. MacIntire, Willis, and Hardy (13) have demonstrated such reaction when magnesium carbonate is added to soils. We have, therefore, a change of carbonate to silicates with a loss of carbon dioxide.

It is evident then that an analysis of a water extract of soils to which salts were added would not show a total recovery of salts as CO_3 and HCO_3. Here it is seen that this unrecovered portion would be considered as absorbed by the soil, but this absorption would on the other hand not be due entirely to the sodium carbonate removed as such by the soil, but would be partly due to the resultant of the interreactions of silicates and carbonates. Such reactions have been shown to take place easily.

Chief among the investigations describing the above cited reactions is the classic work of Lemberg (9), who demonstrated that an exchange of bases can take place between a silicate and salt solution; by the addition of a free base to the silicate from an alkaline solution or by the addition of the entire salt. Sullivan (14, p. 5–36) has developed additional data on the base exchange theory in regard to salts and silicates. He states, "Where the solution is alkaline in reaction, containing a soluble hydroxide dissolved as such or a salt made up of a strong base and a weak acid (as the carbonates, silicates and phosphates of sodium and potassium) which is hydrolyzed by water with resulting formation of free alkali; its behavior with clay, soils, etc., is due largely to the presence of colloid silica or aluminum silicate, and consists primarily in the direct addition of alkali to these solids, without substitution, insoluble silicates or alumino-silicates being found." Armsby (1) has also discussed the nature of absorption of bases by silicates and pointed out that the absorption is in accordance with the law of mass action. He illustrates experimentally the reason that no relation of chemical equivalence existed between the quantity of base taken up and the quantity of any single constituent in the soil. The reason for this was not explained by Way (16) and others when they attempted to use this fact as evidence of a physical surface absorption phenomena rather than a chemical reaction in soil. Henneberg and Stohmann (6) found that the greater the amount of solution of a salt taken with a fixed quantity of soil, the greater was the absorption. In certain cases doubling the amount of solution increased the amount of absorption by one-fifth. E. A. Fisher (3) has assembled and critically discussed the views of several investigators on the absorption phenomena in soils.

Because of the possible reactions which may occur between the soil and an added salt such as sodium carbonate, it is suggested that a part of the additions of sodium carbonate not recoverable in the water extracts may not exist as such in the soil but may have been changed into other forms and may not have been absorbed as sodium carbonate. This conclusion has some support in the fact that the salt additions to the soil gradually come to an equilibrium; very rapidly at first with the more concentrated solutions and then more gradually until only slight changes occur. In the second series with the heavy additions the major equilibrium reactions took place rapidly and varied but slightly during the remaining period of contact. Here it is evident that concentration played a considerable part in the speed with which the general point of equilibrium was reached. It is quite evident that one of the chief factors of equilibrium in soils is the solubility factor of the salts entering into

the reactions but to attempt to fix anything but generalities in the rate of equilibrium reactions in soils would be the utmost folly because of the complexity of the media involved. It appears that the solubility of the silicates in the soils has much to do with the rate of reaction and this in part accounts for the gradual change in equilibrium resulting in a decrease in amount of recoverable salt as time elapses. Slight deviations from time to time might be accounted for by the difficulty of securing uniform samples and by the reversibility of the reactions occurring in the soil.

The three soils are somewhat different in texture. The Palouse silt loam is quite high in organic matter; the Caldwell silt loam subsoil contains considerably more clay than the other two soils; the Boise silt loam borders on a sandy loam. The final recovery of carbonates in general is less with the Caldwell soil containing considerable clay. Very little difference is noted between the other soils. In discussing the bicarbonate recoveries in general it must be said that the reverse of the carbonate series is true.

The entire work tends to show the extreme ability of a soil to establish an equilibrium between added salts even when added in a so-called cumulative manner.

So many factors must be considered in discussing absorption in soils, since soils are so complex and varying in nature that these suggestions on the absorption of carbonates are only offered as tentative explanations. The fact that the recoverable and not added carbonate salts are the criterion for determining toxicity of plants may be partially explained by the fact that the absorbed salts have been changed in part to other forms. Cognizance is taken of the fact that absorption of sodium carbonate *per se* by the finely divided material present in soils may and undoubtedly does take place. This absorption may be classed as mechanical in nature, or purely surface absorption.

SUMMARY

1. Absorption increased rapidly from the initial mixing of salts until a maximum was reached, after which the time of contact had little influence upon the percentage absorption of added salts.

2. After the equilibrium was reached in the first series, additional salts added to these same soils resulted in an equilibrium similar to that established in the first series. A notable feature of the second series of added salts is that the soils responded to these treatments of added carbonates in a manner similar to that of the first series. The soils established an added absorption in a similar degree to that of the first series. How long these soils would show this same capacity for additional absorption can not be stated since these experiments were concluded after two additions of salts.

3. Addition of carbonate salts to soils, immediately showed a portion of the recoverable salts as bicarbonates. The extent of this change depended chiefly upon the individual soil. Bicarbonate additions to moist soils showed recoverable salts determined as normal carbonate after a short period of contact.

4. Within the range of concentrations of salts added, these four soils showed a greater absorption for the greater concentrations of added salt.

5. The four soils were assumed to be widely different at the beginning of the experiment, but at the conclusion, or when equilibrium was established they showed very similar capacities for absorption.

6. Differences of absorption were more noticeable with the four soils when the salts were in contact for short periods indicating that greater absorption takes place when the concentration of salt was the highest.

7. Carbonate and bicarbonate salt treatments to soils maintained in an air-dry condition showed much less absorption than soils maintained at the optimum moisture content. In air-dry soils a part of the carbonates were changed to bicarbonates. Bicarbonate additions were not changed to carbonate in any great degree.

8. It is suggested that a portion of the sodium carbonate, not recovered in the water extract and generally conceded to be absorbed by the soil, is in reality changed into other compounds, which makes it impossible to secure a quantitative recovery.

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THE VARIANT RÔLES OF SOIL AND SUBSOIL IN CALCIUM-MAGNESIUM INTERCHANGE

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INTRODUCTORY

In the expansion of earlier studies upon the activities of the different oxides and carbonates of calcium and magnesium, forty-six lysimeters were installed July, 1914. This equipment has been described and illustrated in previous reports (6, 7) upon certain phases of the general problem. The annual and 8-year losses of calcium and magnesium, both direct and as a result of *subsoil interchange* induced by leachings from excessive additions, are given in this contribution. It will be shown also that excesses of solid-phase calcic and magnesic materials in the surface soil are *reversibly repressive* upon the solubility of native stores of the alkali-earths. Certain calcic and magnesic treatments depressed calcium and magnesium outgo decidedly below corresponding losses from the untreated control. A supplementary article will report leaching data from much smaller amounts of calcic and magnesic materials.

EXPERIMENTAL

Each material, CaO, MgO, $CaCO_3$, $MgCO_3$, limestone, dolomite, and magnesite was used in chemical equivalence at the rates of 8, 32, and 100 tons of CaO per 2,000,000 pounds of moisture-free soil. Each addition was made to surface soil only and to soil underlaid by a 1-foot depth of clay subsoil. One wollastonite and one serpentine addition were also made in deep tanks. All additions were mixed throughout the full depth of the surface soil. The compositions of the additions have been given in a previous (8, p. 2) contribution. The soil used was an acid loam secured from a near-by source. It was protected from drying out during the process of screening, sifting, and admixture of treatment. The surface soil contained 0.18 per cent CaO and 0.30 per cent MgO, while the subsoil contained 0.19 per cent CaO and 0.47 per cent MgO.

Periodic collections of leachings were aliquoted and acidified with HCl to obtain annual composites. One-liter portions of composites were concentrated for the determination of calcium and magnesium by standard methods.

PRESENTATION OF DATA

Each annual and total outgo of calcium from the surface soil alone is shown in juxtaposition to the outgo from surface soil after its passage through subsoil for the additions at the 8-, 32- and 100-ton rates in tables 1, 2, and 3, respectively. Annual and total losses, or retentions, of magnesium are shown in the same manner in tables 4, 5, and 6. Only the totals are considered in this contribution, though nitrates, sulfates, carbonates, bicarbonates and hydroxides have been determined. Since all treatments were based on chemical equivalence. *the losses and increases are expressed throughout as $CaCO_3$-equivalence, for both calcium and magnesium.* The totals and the annual averages for the first and second 4-year periods and for the full 8-year period also are given. In the third from the last column of each of the six tables are given the differences between the total losses from the shallow tanks and those from the corresponding deep tanks. Such differences show the direct losses from the excess of the applied calcic or magnesic material, the amount of applied base stopped by the subsoil, and the increase due to liberation of calcium by the base applied in excess to the surface soil.

OUTGO OF CALCIUM FROM TREATMENTS IN FORTY-SIX TANKS

From burnt lime. The maximum loss from the 8- and 32-ton treatments in the shallow tanks came during the first year. The 100-ton addition gave unusually heavy yields during the first three years, with the maximum for the third year. The loss from the light treatments was due entirely to bicarbonate, nitrate, and sulfate of calcium; but considerable $Ca(OH)_2$ came from the two heavier treatments. More than one-half of the loss from each addition came during the first 4-year period. The total losses during both 4-year periods and during the full period increase in the order of increase of treatment, but not in direct proportion.

The yields from the deep tanks were uniformly less and but a fraction of the yields from corresponding shallow tanks. Differing from the shallow tanks, no $Ca(OH)_2$ has ever passed through the subsoil. Of the totals, 7194, 9530, and 27,349 pounds from the three rates in the shallow tanks, the subsoil caused respective stoppages of 4270, 7174, and 24,566 pounds.

From burnt magnesia. The MgO treatment proved decidedly depressive to the outgo of calcium from the surface soil. The average annual loss from the shallow control was 205 pounds, while the annual losses from the 8-, 32-, and 100-ton MgO additions were 117, 70, and 68 pounds, respectively. By reference to tables 4, 5, and 6 it will be seen that, coincident with depressed calcium outgo, large quantities of soluble salts of magnesium came from the MgO additions, the outgo increasing with rate of addition. It is an established fact that solutions of neutral salts of the alkalies and alkali-earths will effect a liberation of one or more of the soil bases not present in the treatment solution. But the depressive influence of the added MgO upon the surface-

TABLE 1

Amounts of calcium salts leached from a loam soil during an 8-year period—Seven calcic and magnesic additions at rates equivalent to 8 tons of CaO per 2,000,000 lbs. of soil

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TANK NUMBER	TREATMENT	SUBSOIL	$CaCO_3$ EQUIVALENT IN POUNDS PER 2,000,000 POUNDS OF SOIL															
			Annual periods												8-year period			Average annual variation from shallow and deep control tanks
			First year	Second year	Third year	Fourth year	First 4-year period		Fifth year	Sixth year	Seventh year	Eighth year	Second 4-year period		Average annual	Total	Subsoil stopped or yielded	Increase / Decrease
							Average annual	Total					Average annual	Total				
1	CaO	None	1767	1062	1009	446	1071	4284	732	764	630	784	728	2910	899	7194	Stopped	694
22		Clay	499	408	410	197	379	1514	305	391	328	386	353	1410	366	2924	4270	265
2	MgO	None	180	74	164	61	120	479	123	107	105	121	114	456	117	935	Yielded	88
23		Clay	439	477	442	195	388	1553	306	422	287	374	347	1389	368	2942	2007	267
3	$CaCO_3$	None	1406	831	913	453	901	3603	749	750	668	823	748	2990	824	6593	Stopped	619
24		Clay	350	350	435	174	327	1309	383	483	284	375	381	1525	354	2834	3759	253
4	$MgCO_3$	None	189	79	145	56	117	469	113	75	113	128	107	429	112	898	Yielded	93
25		Clay	388	470	551	180	397	1589	293	432	278	308	328	1311	363	2900	2002	262
5	Limestone	None	1730	818	929	394	968	3871	727	757	724	810	755	3018	861	6889	Stopped	656
26		Clay	279	407	423	187	324	1296	320	387	285	352	336	1344	330	2640	4249	229
6	Dolomite	None	756	442	395	216	452	1809	455	432	403	490	445	1780	449	3589	Stopped	244
27		Clay	233	382	366	135	279	1116	260	334	264	292	288	1150	283	2266	1323	172
7	Magnesite	None	402	155	131	58	187	746	112	83	117	166	120	478	153	1224	Yielded	52
28		Clay	350	436	365	133	321	1284	225	226	236	267	239	954	280	2238	1014	179
46	None	None	280	112	214	299	224	905	122	204			163*	326*	205†	1231†	Stopped	
45		Clay	142	41	87	181	113	451	65	87			76*	152*	101†	603†	628†	
Rainfall in inches			47.78	56.54	63.32	47.79	53.86		51.41	54.21	50.37	55.63	52.91		53.38			

* 2-year average

† 6-year period only.

TABLE 2

Amounts of calcium salts leached from a loam soil during an 8-year period—Nine calcic and magnesic additions at rates equivalent to 32 tons of CaO per 2,000,000 lbs. of soil

TANK NUMBER	TREATMENT	SUBSOIL	$CaCO_3$ EQUIVALENT IN POUNDS PER 2,000,000 POUNDS OF SOIL															
			Annual periods												8-year period			Average annual variation from shallow and deep control tanks
			First year	Second year	Third year	Fourth year	First 4-year period		Fifth year	Sixth year	Seventh year	Eighth year	Second 4-year period		Average annual	Total	Subsoil stopped or yielded	Increase / Decrease
							Average annual	Total					Average annual	Total				
8	CaO	None	2601	1255	1355	478	1422	5689	753	1129	971	988	960	3841	1191	9530	Stopped	986
29		Clay	133	569	551	179	358	1432	235	256	207	226	231	924	295	2356	7174	194
9	MgO	None	147	21	33	29	58	230	81	15	98	85	70	279	64	509	Yielded	141
30		Clay	163	1033	719	171	522	2086	206	300	170	191	217	867	369	2953	2444	268
10	$CaCO_3$	None	1309	820	1021	417	892	3567	730	849	718	796	773	3093	833	6660	Stopped	628
31		Clay	228	355	313	148	261	1044	258	331	281	322	298	1192	255	2236	4424	154
11	$MgCO_3$	None	130	50	89	41	78	310	85	69	100	90	86	344	82	654	Yielded	123
32		Clay	573	851	841	199	616	2464	287	399	200	229	279	1115	448	3579	2925	347
12	Limestone	None	1330	825	951	445	888	3551	788	752	708	842	773	3090	830	6641	Stopped	625
33		Clay	241	367	335	146	272	1089	296	373	286	309	316	1264	294	2353	4288	193
13	Dolomite	None	1059	686	738	303	697	2786	585	724	510	643	616	2462	656	5248	Stopped	451
34		Clay	278	345	423	167	303	1213	299	419	319	386	356	1423	330	2636	2612	229
14	Magnesite	None	270	131	200	85	172	686	142	158	146	152	150	598	161	1284	Yielded	44
35		Clay	318	389	551	201	365	1459	355	513	319	351	385	1538	375	2997	1713	274
43	Wollas*	Clay	142	367	342	159	253	1010	229	378	267	389	316	1263	284	2273	1471†	183
44	Serp.*	Clay	188	220	259	102	192	769	112	268	174	237	198	791	195	1560	758†	94
Rainfall in inches..			47.78	56.54	63.32	47.79	53.86		51.41	54.21	50.37	55.63	52.91		53.38			

* Actual rate of 32 tons of material.

† Yield in excess of 8-year loss from deep control tank 45, 8-year basis.

* Actual rate of 32 tons of material.

† Yield in excess of 8-year loss from deep control tank 45, 8-year basis.

TABLE 3

Amounts of calcium salts leached from a loam soil during an 8-year period—Seven calcic and magnesic additions at rates equivalent to 100 tons of CaO per 2,000,000 lbs. of soil

TANK NUMBER	TREATMENT	SUBSOIL	$CaCO_3$ EQUIVALENT IN POUNDS PER 2-000,000 POUNDS OF SOIL															
			Annual periods												8-year period			Average annual variation from shallow and deep control tanks
			First year	Second year	Third year	Fourth year	First 4-year period		Fifth year	Sixth year	Seventh year	Eighth year	Second 4-year period		Average annual	Total	Subsoil stopped or yielded	Increase / Decrease
							Average annual	Total					Average annual	Total				
15	CaO	None	5176	5725	8101	1641	5161	20643	2751	1454	1365	1136	1677	6706	3419	27349	Stopped	3214
36		Clay	159	506	460	201	332	1326	548	345	286	278	364	1457	696	2783	24566	247
16	MgO	None	241	57	42	7	87	347	61	61	76	72	68	270	77	617	Yielded	128
37		Clay	206	679	707	133	431	1725	402	779	387	360	482	1928	457	3653	3036	356
17	$CaCO_3$	None	1278	999	913	385	894	3575	658	685	706	675	681	2724	788	6299	Stopped	583
38		Clay	172	386	346	237	285	1141	369	451	329	350	375	1499	330	2640	3659	229
18	$MgCO_3$	None	125	365	44	26	140	560	74	88	89	93	86	344	113	904	Yielded	92
39		Clay	236	899	1088	126	587	2349	300	306	191	220	254	1017	421	3366	2462	320
19	Limestone	None	1603	859	990	391	961	3843	724	782	694	696	724	2896	842	6739	Stopped	637
40		Clay	347	418	267	143	294	1175	271	425	313	309	330	1318	312	2493	4246	211
20	Dolomite	None	1262	741	832	332	792	3167	701	760	648	713	706	2822	749	5989	Stopped	544
41		Clay	233	291	269	133	232	926	466	594	440	566	517	2066	374	2992	2997	273
21	Magnesite	None	419	172	217	79	222	887	147	165	160	176	162	648	192	1535	Yielded	13
42		Clay	196	419	432	182	307	1229	345	464	342	328	370	1479	376	2708	1173	275
Rainfall in inches			47.78	56.54	63.32	47.79	53.86		51.41	54.21	50.37	55.63	52.91		53.38			

TABLE 4

Amounts of magnesium salts salts leached from a loam soil during an 8-year period—Seven calcic and magnesic additions at rates equivalent to 8 tons of CaO per 2,000,000 lbs. of soil

TANK NUMBER	TREATMENT	SUBSOIL	$CaCO_3$ EQUIVALENT IN POUNDS PER 2,000,000 POUNDS OF SOIL																
			Annual periods												8-year period			Average annual variation from shallow and deep control tanks	
			First year	Second year	Third year	Fourth year	First 4-year period		Fifth year	Sixth year	Seventh year	Eighth year	Second 4-year period		Average annual	Total	Subsoil stopped or yielded	Increase	Decrease
							Average annual	Total					Average annual	Total					
1	CaO	None	112	61	36	39	62	248	44	84	59	55	61	242	61	490	Yielded		45
22		Clay	279	300	323	165	267	1067	260	444	267	270	310	1241	269	2308	1818	132	
2	MgO	None	2274	1346	1448	570	1410	5638	817	998	613	723	788	3151	1099	8789	Stopped	993	
23		Clay	239	361	374	252	307	1226	240	418	276	334	317	1268	312	2494	6295	175	
3	$CaCO_3$	None	149	58	74	48	82	329	48	172	59	36	79	315	81	644	Yielded		25
24		Clay	184	250	356	205	249	995	301	487	307	304	350	1399	299	2394	1750	162	
4	$MgCO_3$	None	3525	1791	1569	631	1879	7516	787	977	712	759	809	3235	1344	10751	Stopped	1228	
25		Clay	210	338	480	231	315	1259	298	504	330	368	375	1500	345	2759	7992	208	
5	Limestone	None	163	71	71	37	86	342	53	149	43	107	88	352	87	694	Yielded		19
26		Clay	171	293	369	142	244	975	240	403	270	262	294	1175	269	2150	1456	132	
6	Dolomite	None	484	384	345	195	352	1408	351	468	320	463	401	1602	376	3010	Stopped	270	
27		Clay	161	276	350	146	233	933	229	352	239	246	267	1066	250	1999	1011	113	
7	Magnesite	None	1595	1064	1139	533	1083	4331	789	1043	716	791	835	3339	959	7670	Stopped	853	
28		Clay	205	343	358	170	269	1076	212	272	216	255	239	955	254	2031	5539	117	
46	None	None	126	94	70	136	107	426	80	128			104	208*	106†	634†	Yielded		
45		Clay	226	86	133	208	163	653	78	89			84	167*	137†	820†	186†		
Rainfall in inches..			47.78	56.54	63.32	47.79	53.86		51.41	54.21	50.37	55.63	52.91		53.38				

* Two years.
† Six years.

TABLE 5

Amounts of magnesium salts leached from a loam soil during an 8-year period—Nine calcic and magnesic additions at rates equivalent to 32 tons CaO per 2,000,000 lbs. of soil

* Two years.
† Six years.

TABLE 5

Amounts of magnesium salts leached from a loam soil during an 8-year period—Nine calcic and magnesic additions at rates equivalent to 32 tons CaO per 2,000,000 lbs. of soil

TANK NUMBER	TREATMENT	SUBSOIL	$CaCO_3$ EQUIVALENT, IN POUNDS PER 2,000,000 POUNDS OF SOIL																
			Annual periods												8-year period			Annual average variation from shallow and deep control tanks	
			First year	Second year	Third year	Fourth year	First 4-year period		Fifth year	Sixth year	Seventh year	Eighth year	Second 4-year period		Average annual	Total	Subsoil stopped or yielded	Increase	Decrease
							Average annual	Total					Average annual	Total					
8	CaO	None	73	51	26	43	48	193	88	130	48	65	83	331	66	524	Yielded		40
29		Clay	88	432	508	167	299	1195	220	299	196	181	224	896	261	2091	1567	124	
9	MgO	None	3749	5034	4869	1735	3847	15387	1595	2037	1455	1372	1615	6459	2731	21846	Stopped	2625	
30		Clay	119	884	2105	762	968	3870	866	1575	1339	933	1178	4713	1073	8583	13263	936	
10	$CaCO_3$	None	114	84	91	55	86	344	33	166	68	90	89	357	88	701	Yielded		18
31		Clay	152	272	304	139	217	867	215	404	302	279	300	1200	258	2067	1366	121	
11	$MgCO_3$	None	3878	3944	4969	2678	3867	15469	3403	4081	3246	3410	3535	14140	3701	29609	Stopped	3595	
32		Clay	390	865	2306	1806	1342	5367	1689	3290	2241	2068	2323	9288	1832	14655	14954	1695	
12	Limestone	None	148	82	93	64	97	387	84	318	97	100	125	499	111	886	Yielded	5	
33		Clay	157	276	287	139	215	859	236	408	272	216	283	1132	249	1991	1105	112	
13	Dolomite	None	525	383	442	173	380	1523	298	490	276	368	358	1432	372	2975	Stopped	266	
34		Clay	211	288	390	167	264	1056	262	395	293	294	311	1244	288	2300	675	151	
14	Magnesite	None	1138	1095	1361	671	1066	4265	888	1212	836	945	970	3881	1018	8146	Stopped	912	
35		Clay	237	313	489	288	332	1327	311	441	301	328	345	1381	339	2708	5438	202	
43	Wollas.*	Clay	176	298	352	150	244	976	229	396	273	326	306	1224	275	2200	1109†	138	
44	Serp.*	Clay	94	194	250	150	172	688	112	292	173	231	202	808	187	1496	405†	50	
Rainfall in inches			47.78	56.54	63.32	47.79	53.86		51.41	54.21	50.37	55.63	52.91		53.38				

* Actual rate of 32 tons of material.
† Yield in excess of 8-year loss from deep control.

TABLE 6

Amounts of magnesium salts leached from a loam soil during an 8-year period—Nine calcic and magnesic additions at rates equivalent to 100 tons CaO per 2,000,000 lbs. of soil

TANK NUMBER	TREATMENT	SUBSOIL	$CaCO_3$ EQUIVALENT, IN POUNDS PER 2,000,000 POUNDS OF SOIL																
			Annual periods												8-year period			Annual average variation from shallow and deep control tanks	
			First year	Second year	Third year	Fourth year	First 4-year period		Fifth year	Sixth year	Seventh year	Eighth year	Second 4-year period		Average annual	Total	Subsoil stopped or yielded	Increase	Decrease
							Average annual	Total					Average annual	Total					
15	CaO	None	71	37	51	20	45	179	42	133	35	44	64	254	54	433	Yielded		52
36		Clay	140	380	402	503	356	1425	324	324	310	145	276	1103	316	2528	2095	179	
16	MgO	None	2002	3456	3377	1216	2513	10051	3046	5494	3999	3246	3946	15785	3220	25836	Stopped	3114	
37		Clay	181	520	648	562	478	1911	929	4035	3639	2848	2863	11451	1670	13362	12474	1533	
17	$CaCO_3$	None	258	240	163	58	180	719	89	225	101	124	135	539	157	1258	Yielded	51	
38		Clay	120	279	299	208	227	906	284	462	307	283	334	1336	280	2242	984	143	
18	$MgCO_3$	None	4537	5048	6018	2238	4460	17841	3719	5149	3886	3897	4163	16651	4312	34492	Stopped	4206	
39		Clay	179	700	2938	1896	1428	5713	2739	4450	3605	3220	3504	14014	2466	19727	14765	2329	
19	Limestone	None	214	105	168	56	136	543	90	127	109	95	105	421	121	964	Yielded	15	
40		Clay	257	349	294	132	258	1032	245	423	290	292	313	1250	285	2282	1318	148	
20	Dolomite	None	525	382	407	163	369	1477	307	443	304	336	348	1390	358	2867	Stopped	252	
41		Clay	137	251	287	134	202	809	378	522	340	146	347	1386	274	2195	672	137	
21	Magnesite	None	1323	1084	1316	564	1072	4287	784	1111	812	896	901	3603	986	7890	Stopped	880	
42		Clay	100	333	413	212	265	1058	307	487	357	350	375	1501	319	2559	5340	182	
Rainfall in inches.....			47.78	56.54	63.32	47.79	53.86		51.41	54.21	50.37	55.63	52.91		53.38				

soil outgo under field conditions, intimate admixture of the solid phase and diffusion of the bicarbonate and neutral salts of magnesium, is different from the results to be anticipated when excess of dissolved salts are agitated with surface soil and is not in harmony with the accepted concept relative to liberation of calcium by an excess of magnesium. It is in harmony, however, with previous lysimeter findings (7, 10), in which it was shown that magnesic, and also calcic materials proved depressive, rather than liberative, to the outgo of potassium salts.

The reverse condition obtained when the magnesium leachings from the surface soil passed through the subsoil. Without exception, all twenty-four annual-leaching composites from the MgO additions in the deep tanks carried decidedly larger amounts of calcium than those leached from the corresponding shallow tanks. Furthermore, *the $CaCO_3$ liberated by the 8-ton MgO treatment was greater than the $CaCO_3$ recovery from the 8-ton CaO addition and still greater than that from the addition of $CaCO_3$ at the same rate. The two heavier MgO additions both liberated still more of $CaCO_3$ from the subsoil than was obtained as recoveries as soil-subsoil leachings from either the 32- or 100-ton additions of CaO and $CaCO_3$.* For the total period, the accumulations of $CaCO_3$ during the movement of leachings through the subsoil were 2007, 2444, and 3036 pounds, respectively, for the 8-, 32-, and 100-ton MgO additions. These results give corresponding annual averages of 251, 306, and 380 pounds $CaCO_3$-equivalence, as representing the cumulative effect of the subsoil with influx of magnesium salts, as against the 101-pound average annual loss, or about one-half of the 205-pound increment leached to it from the untreated surface soil. Applying the actual blank of the deep tank, the average annual yields of $CaCO_3$ from the subsoil appear as 267, 268, and 356 pounds, for the three additions, in order.

The difference between the shallow- and deep-tank calcium losses from MgO treatments are so striking and consistent as to warrant some attempt at explanation. Several possibilities suggest themselves. In view of the insolubility of $Mg(OH)_2$, it may be assumed that the depression exerted by solution phases are to be attributed rather to the bicarbonate, nitrate, or sulfate of magnesium. If the calcium content of the subsoil were greater than that of the surface soil there would be expected a greater $CaCO_3$ liberation. But the respective contents of 0.18 per cent and 0.19 per cent eliminate this consideration as a causative factor. Again it may be that the solubility of the calcium compounds in the subsoil is greater than that of those in the surface soil, the subsoil being uniformly in a more hydrolytic condition. On the other hand, the conditions under which the added material is brought into contact with the soil mass through solution varies for the upper and lower soil. The surface zone of the soil often may be so dry as to preclude free movement of solvent and solute, and when free movement does obtain after rainfall, it is more rapid and the period of contact is therefore of less duration than in the case of the subsoil. Furthermore, the volume of the subsoil

stratum is greater, the subsoil depth being 12 inches as against approximately 8 for the surface soil. It may be, therefore, that the difference between non-replacement in the surface soil and interchange in the subsoil is due largely to difference in bulk and to the time factor. The lysimeter results demonstrate the facts as found under the experimental conditions, with emphasis upon excessive treatment, but supplementary laboratory investigations are necessary and are now in progress, to clarify the problem.

From calcium carbonate. The three rates show close concordance where the precipitated material was used as a control against the burnt lime in the shallow tanks. The period averages and the totals show but little variation as a result of the range of the treatment from 8 to 100 tons. The three totals of 6593, 6660, and 6290 pounds indicate that the 8-ton addition was so uniformly disseminated throughout the mass of the soil as to insure maximum solvent action under the prevailing conditions. Assuming an H_2CO_3 constant, the somewhat smaller outgo from the 100-ton treatment may be assigned to physical causes incident to the increase in bulk resultant from the heavy addition. Each of the three additions gave surface-soil losses less than those obtained from the respective CaO equivalents. The greater disparities, which followed increase in rate were due more to the leachings of $Ca(OH)_2$ from the CaO than to any lack of equivalence in outgo of calcium bicarbonate. Each annual outgo through the subsoil was distinctly less than the amount obtained from the surface soil alone. The subsoil stopped $CaCO_3$ at the rates of 2759, 4424, and 3659 pounds, respectively, for the 8-, 32-, and 100-ton additions. As pointed out in a previous contribution (8), this agreement between yields from the 8- and 100-ton treatments, the slower movement, smaller outgo, and greater retention by the subsoil were consistent, the same relationships obtaining, so far as determined, for nitrate and sulfate of calcium, as well as bicarbonate.

From magnesium carbonate. Magnesium carbonate exerted the same positive depressive influence as that exerted by MgO upon the outgo of calcium from the surface soil, though on the whole not to the same degree. In no case did the total $CaCO_3$ yield from the $MgCO_3$-treated soil approach that from the untreated surface soil. Again, as in the MgO tanks, the $MgCO_3$ treatment effected a distinct liberation of $CaCO_3$ from the subsoil, so that *the $CaCO_3$ passing from the $MgCO_3$ tank was actually greater than that from the tank which received $CaCO_3$ at the 8-ton rate. This was also true, to an even greater extent, in the case of the 32- and 100-ton additions.* On the previously mentioned assumption that applied MgO is inactive as the hydroxide because of the meager amounts of $Mg(OH)_2$ carried in the free soil water, and that the depression in calcium outgo is caused by bicarbonate, nitrate, and sulfate of magnesium, the discussion devoted to the ougto of calcium salts from MgO additions is applicable also to leachings from the $MgCO_3$ additions.

From 100-mesh limestone. The 100-mesh limestone, containing 94.33 per cent $CaCO_3$ and 1.62 per cent $MgCO_3$, gave a $CaCO_3$ yield intermediate be-

tween that from CaO and that from the precipitated carbonate at the 8-ton rate in the shallow tanks. The total recoveries of 6889, 6641, and 6739 pounds from the 8-, 32-, and 100-ton treatments show that no increase in outgo resulted from increase in rate of application. In like manner the several amounts arrested by the subsoil demonstrate the uniformity of its tendency to absorb when it receives comparable amounts from the surface-soil leachings. From the surface-soil yields of 6889, 6641, and 6739 pounds of $CaCO_3$ for the treatments, in order, 4249, 4288, and 4246 pounds were stopped.

From 100-mesh dolomite. The dolomite contained 49.96 per cent $CaCO_3$ 39.11 per cent $MgCO_3$. The amounts of $CaCO_3$ leached from it were therefore uniformly less as annuals and totals for the shallow tanks. Differing from the leachings from limestone additions, the dolomite additions gave increased outgo of calcium with increase in treatment. Although the amounts from the shallow tanks were uniformly more than those from the corresponding deep tanks, for all three rates, the differences were not so large as those which were found in the limestone series. With increase in rate, there was an increase also in the amount of $CaCO_3$ removed from solution by the subsoil, the 8-, 32-, and 100-ton additions having shown removals of 1323, 2612, and 2992 pounds, respectively.

From 100-mesh magnesite. The less soluble magnesite did not show so extensive a retardation in $CaCO_3$ outgo from the surface soil as that shown by MgO and by $MgCO_3$ at the three rates. Nevertheless, the totals and annual averages showed positive depressive influences. Such were in effect more particularly after the first two years. The deep tanks showed $CaCO_3$ losses consistently greater than those found for the corresponding shallow tanks and also controls. The average total of $CaCO_3$ increase from the subsoil was comparable to the outgo from the soil, practically one-half of the amount leached from the 8-ton additions of MgO and $MgCO_3$, and 35.8 per cent of that derived by the solution and leaching of the corresponding $CaCO_3$ addition to the surface soil. Differing from the MgO, which gave increased liberation with increase in rate, and agreeing with the $MgCO_3$, the largest outgo of $CaCO_3$ from the subsoil came from the 32-ton treatment, which yielded 1713 pounds, as against 1014 pounds and 1173 pounds for the 8- and 100-ton additions respectively.

From 100-mesh wollastonite and serpentine. These two materials were used only in the deep tanks. The wollastonite contained 45.11 per cent CaO, 0.48 per cent MgO, and 0.69 per cent CO_2, while the serpentine contained 0.09 per cent CaO, 37.79 per cent MgO, and 0.14 per cent CO_2. After the first year all composites of leachings from the wollastonite carried more calcium salts than did the corresponding composites from serpentine. However both materials gave a larger annual average outgo of $CaCO_3$ than that from the deep control tank—284 pounds, 195 pounds, and 101 pounds for wollastonite, serpentine, and control, respectively. It is thus apparent that some of the wollastonite-derived calcium salts passed through the subsoil and

that the serpentine-derived magnesium compounds liberated each year about 100 pounds of $CaCO_3$ from soil, or subsoil, or both. Since magnesite exerted the same depressive tendency manifested by the more rapidly dissolved MgO and $MgCO_3$ upon the outgo of calcium salts from the surface soil, it is more probable that the increase in $CaCO_3$ above the yield from the control was due to an interchange induced in the subsoil by the serpentine-derived magnesium salts. When calculated to an 8-year loss, the outgo of 802 pounds of $CaCO_3$-equivalence falls 1471 pounds short of that from the wollastonite. In the same manner, an increase of 758 pounds is attributed to the magnesium silicate of the serpentine. For each $CaCO_3$-pound-equivalent leached from the surface and through the subsoil, there was an interchange yield of 0.515 pound induced by the serpentine.

OUTGO OF MAGNESIUM FROM FORTY-SIX TANKS

It is readily conceded that a solution of neutral salts will effect an interchange of magnesium in the components native to the soil. Very few data are available, however, as to the activity of CaO and $CaCO_3$ under conditions comparable to those of the field.

MacIntire (5) analyzed the three upper 7-inch zones of the limed plots of the Pennsylvania Experiment Station, after thirty-years of cumulative liming. The samples analyzed were composites of the plots of tiers 1–4, which received burnt lime, burnt lime plus manure, and ground limestone. It is of course admitted that the results so obtained were subject to the error incident to the sampling of so large a total area—one-half acre—for each treatment and to the variation in soil type. The ultimate analyses showed, however, that both lime and limestone had caused a uniform decrease in residual magnesium. The magnesium content of the check plots, and also that of the composites from both forms of lime, increased with depth. This indicated that the treatment had been of effect in the surface soil and of minimum effect upon the subsoil; or that it had been of effect in the surface soil with the subsoil showing stoppage of part of the induced loss from the surface. Lyon and Bizzel (3) found that applications of lime increased the magnesium content in the leachings from a Dunkirk clay loam in 4-foot tanks. Their results are consistent as indicating basic exchange in some zone, or all zones, of the 4-foot depth, the magnesium content of which increases with increase in depth. They do not determine, however, whether the magnesium was derived from the surface or subsoil. The same investigators found similar evidence of basic exchange in studies with 4-foot depths of Volusia silt loam, which differed from the Dunkirk soil in that the three subsoil strata contained less magnesia than did the surface soil.

From burnt lime. The outgo of magnesium salts from the three CaO additions in the shallow tanks was uniformly less than that of the shallow control. The 8-year totals of 490, 524, and 433 pounds for the 8-, 32-, and 100-ton additions represent average annual leachings of 61, 66, and 54 pounds, respectively, as against 106 pounds from the control. The three lime treatments therefore caused annual conservations of 45, 40, and 52 pounds, respectively. The consistent depressive influence was changed, however, to an accelerative activity when the dissolved calcium salts reached the subsoil. Each of the twenty-four annual leachings from the soil-subsoil tanks carried

a magnesium content greater than that from the corresponding surface tank and a decided excess over the outgo from the control. The amounts of magnesium salts forced from the subsoil, as shown by the differences between surface soil and soil-subsoil leachings, were 1818, 1567, and 2095 pounds, respectively, or annual averages of 132, 124, and 179 pounds in *excess* of the control for the 8-, 32-, and 100-ton additions.

The unabsorbed portion of the 8-ton CaO treatment remained in the hydrate form only a short time, but hydrate excesses were present for over three years where the heavier additions of 32 tons and 100 tons were made, as was shown by periodic residual carbonate determinations and by the determination of $Ca(OH)_2$ in leachings. But such occurrences failed to show any liberation of magnesium from the surface soil. It could not be assumed that there occurred a liberation of magnesium as the hydrate and that in this insoluble form the magnesium was retained by the soil. For since the MgO parallel demonstrated that large quantities of MgO were carbonated and leached, much if not all of such assumed $Mg(OH)_2$ would have leached as the bicarbonate after the conversion of the insoluble magnesium hydrate into hydroxide and then into the soluble bicarbonate, thereby showing a larger magnesium outgo during the second 4-year period. However, the losses during the second 4-year period were relatively the same as those of the first 4-year period. Furthermore, the calcium carbonate influenced magnesium outgo in the same manner. Again, if the repressive action were to be considered as due to mechanical protection afforded the native magnesic components by the added calcic forms, the much heavier additions of oxide and carbonate at the 32- and 100-ton rates would be expected to be still more retardative than the 8-ton rate; but such proved not to be the case. Although plausible viewpoints might be advanced to explain the failure of the soluble hydrate and the lesser soluble carbonate of calcium to liberate magnesium from the soil, it is difficult to account for the fact that instead of liberation, or non-liberation, there was a positive and consistent removal of magnesium from the solution phase in the soil mass.

From burnt magnesia. The most rapid outgo of magnesium salts from the 8-ton treatment came during the first three years, with the maximum during the first year. A large part of the loss from the surface soil was stopped by the layer of subsoil during each of the eight years. From a comparison of the totals of 8789 pounds and 2494 pounds from the shallow and deep tanks, respectively, it appears that the subsoil retained 6295 pounds of soluble magnesium salts. Similar differences from the 32-ton and 100-ton additions show the subsoil to have absorbed 13,263 pounds from the former and 12,474 pounds from the latter. The $MgO\text{-}CO_2\text{-}H_2CO_3$ balances of the two heavier treatments differed from that of the 8-ton addition and between themselves, in the shallow-tank leachings. The greatest yearly losses from the 32-ton treatments came during the first three years, as was true of the 8-ton yield; but both the second and third years' losses were in excess of the loss of the

initial year. During the next five years the losses varied from a minimum of 1372 pounds during the eighth year to a maximum of 2037 pounds during the sixth year. But the 2002-pound outgo from the 100-ton treatment during the initial year was the smallest of the losses of the first three years and but two-thirds of the minimum of the annual losses of the second 4-year period. The total outgo from the 32-ton shallow tank was 1½ times greater than that from the shallow 100-ton tank for the first 4-year period, but for the second 4-year period only about 40 per cent of that from the 100-ton treatment. These differences are most probably due to the fact that the excess of oxide in the larger treatment accounted for the CO_2 available by the formation of more $MgCO_3$ and less $MgH_2(CO_3)_2$ than in the 32-ton treatment.

The soil-subsoil leachings from the 8-ton addition showed more uniformity in magnesium content throughout the 8-year period than did either of the two heavier additions. After the minimum of the initial year the movement from the 32-ton addition increased decidedly, with maintenance of a larger-proportion relationship to the outgo from the surface soil. Following the minimum of the initial year, the 100-ton addition gave about threefold increases during the succeeding 3 years. The losses for the second, third, and fourth years, however, were *less* than the corresponding losses from the 32-ton addition. A distinct increase in magnesium leachings from the 100-ton deep tanks occurred during the fifth year, but the still larger increases during the last three years of the 8-year period were such as to cause the subsoil leachings of magnesium to approach those from the surface soil. With this tendency maintained, the 100-ton losses will soon equal and surpass those from the 32-ton additions. It was interesting to observe during the progress of the investigation that the presence of distinct increases in both neutral salts and bicarbonate of magnesium appeared in the subsoil leachings of the 32-ton addition before such were noted in the leachings from either the 8-ton or 100-ton additions.

From calcium carbonate. After the first year, the $CaCO_3$ treatments at the 8- and 32-ton rates showed the same tendency as that exerted by CaO in depressing the outgo of magnesium from the shallow tanks. The average annual losses from these two rates were 81 pounds and 88 pounds, as against 106 pounds from the shallow control, corresponding to annual depressions of 25 pounds and 18 pounds. The average annual loss of 157 pounds of $CaCO_3$ from the 100-ton shallow tank shows that an annual liberation of 51 pounds was effected by the 100-ton treatment. The average annual losses for the first and second 4-year periods were in close agreement, 82 pounds and 81 pounds for the 8-ton addition and 86 pounds and 88 pounds for the 32-ton addition.

The outgo of magnesium through each deep tank was larger than that from the corresponding shallow tank during each of the eight annual periods for both 8- and 32-ton additions and for the last seven of the eight annual periods in the case of the 100-ton treatments. The amounts of magnesium forced

out from the subsoil by the influx of surface-soil calcium salts came in the order of 8, 100, and 32 tons. Because of the larger amount of magnesium leached from 100-ton treatment in the surface soil, however, the amounts of magnesium derived from the subsoil come in the order of 8, 32, and 100 tons. The average annual supplements to the leachings from the surface soil, as supplied by the subsoil, were 31 pounds for the subsoil control and 218 pounds, 170 pounds, and 123 pounds where the influences of the 8-, 32-, and 100-ton additions were, respectively, of effect. The actual annual increases above the outgo from the control were 162 pounds, 121 pounds, and 143 pounds for the additions, in order.

From magnesium carbonate. By far the largest annual outgo of magnesium from the 8-ton addition of this treatment in the shallow tank was obtained during the first year. Approximately 70 per cent of the total outgo for the 8 years was obtained during the first 4-year period. The major portion of the outgo came as a result of the hydrolysis of magnesium silicates, the full addition of the carbonate soon having been converted to those forms. Five of the eight annual yields from the 32-ton addition to the shallow tank were in excess of the initial and maximum annual outgo from the 8-ton addition; while the remaining three annual losses were far in excess of the next to the largest annual outgo from the 8-ton addition. The excess of magnesium carbonate at this rate was such as to afford large quantities of the hydrated carbonate for solution in the free soil water. Of the grand total outgo, 52.2 per cent was obtained during the first four years. With the exception of the fourth year, each annual ougo from the 100-ton addition was in excess of the corresponding annual yield from the 32-ton addition. Of the 8-year surface-soil loss of 34,492 pounds for the 8-year period, 17,841 pounds, or 51.7 per cent, passed out during the first 4-year period. The actual annual outgo induced by treatment, as determined by subtraction of the average annual outgo of the surface control, was 1228 pounds for the 8-ton addition, 2595 pounds for the 32-ton addition, and 4206 pounds for the 100-ton addition.

Though the several magnesium salts were readily derived from the non-carbonate forms resultant from the absorption of the 8-ton addition in surface soil, they were in large part absorbed by the subsoil, without evidence of any diminution in this property at the end of the 8-year period. Nevertheless, the absorption by the subsoil was not absolute, for the 345-pound annual average outgo was 208 pounds in excess of the 137-pound loss from the control. Although the stoppage by the subsoil was much greater for the 32-ton and 100-ton additions than for the 8-ton addition, the proportion between losses from soil and soil-subsoil were not so large for the heavier additions Of the totals of 10,751, 29,609, and 34,492 pounds which passed from the additions of 8, 32, and 100 tons, respectively, in the surface soil, the amounts retained by the subsoil—7992, 14,954, and 14,765 pounds—represented respective per cent equivalents of 74.3, 50.5, and 42.8. The average annual

increases in outgo above the loss from the deep control were 208, 1695, and 2329 pounds for the three treatments, in order. The amounts of treatment leachings absorbed during the first 4-year period were greater, for each rate, than the corresponding amounts retained during the second 4-year period. The subsoil absorbed during the first 4 years 6257, 10,102, and 12,128 pounds from 8, 32, and 100 tons, respectively, as against 1735, 4852, and 2637 pounds, during the second 4-year interval.

From 100-mesh limestone. The general tendency of the 8-ton-limestone addition was to depress the outgo of magnesium from the surface soil, the annual average of 87 pounds being less than that of 106 pounds from the control. In agreement with $CaCO_3$, the addition of the maximum amount caused a reversal in this relationship, while the yield from the 32-ton addition was very close to that from the untreated soil.

Applying the average annual outgo from shallow control to the three treatments, in order, depression of 19 pounds per annum was shown for the 8-ton addition and increases of 5 and 15 pounds, respectively, for the two heavier amounts.

After the first year all of the subsoil leachings from limestone at the three rates carried more magnesium than did those from the corresponding surface soil, and also more than those from the soil-subsoil control. With increasing order of treatment the yields of magnesium from the subsoil were 1456, 1105, and 1318 pounds. After deduction of the average annual from the deep tank, these three amounts represent actual subsoil releases of 132, 112, and 148 pounds per annum, respectively.

From 100-mesh dolomite. All annual losses from the surface soil which received the three dolomite treatments were in excess of the corresponding losses from the shallow control. Increase in rate of additions gave no increases in total outgo from the surface soil. The totals of 3010, 2975, and 2867 pounds for the 8-, 32-, and 100 ton treatments, respectively, represent average annual losses of 376, 372, and 358 pounds, as against 106 pounds from the control, or net corresponding losses of 270, 266, and 252 pounds.

The subsoil leachings from the dolomite are distinctive, as differing from those of the other eight oxide, carbonate, and silicate forms. In all of the other eight materials either calcium or magnesium was a preponderant component and this relationship obtained in their carbonated-water solutions. As a result, there was in every case a yield of one base and stoppage of the other, as will be seen by comparisons between the third from the last columns of tables 1 and 4, 2 and 5, and 3 and 6. But the $CaCO_3$ and $MgCO_3$ content of the dolomite were on a near-parity. The magnesium carbonate content of 39.11 per cent, equivalent to 46.42 per cent $CaCO_3$, gives a ratio of 1:1.08. Carbonated water extractions of this dolomite showed that the two carbonates dissolved in practically the proportion in which they occur in the rock. There was therefore a stoppage of both calcium and magnesium by the subsoil underlying 3 of the 6 dolomite additions. It is interesting to observe that the surface-

soil losses of magnesium from the dolomite additions were not correlated with rates, and that the calcium outgo increased with increase in treatment. Without deduction of the yield from the shallow control, the ratio of magnesium, in chemical equivalence, found in the leachings was 1:1.19 for the 8-ton addition, 1:1.76 for 32 tons, and 1:2.09 for 100 tons. Applying correction for the average annual of magnesium and calcium from the control, the ratios of $MgCO_3$ to $CaCO_3$, based on chemical equivalence, are 1:0.90, 1:1.70, and 1:2.08 for the 8-, 32-, and 100-ton additions, respectively. In the deep-tank leachings, the ratios of $MgCO_3$ to $CaCO_3$, on chemically equivalent basis, were found to be 1:1.13, 1:1.15, and 1:1.36 for 8, 32, and 100 tons, respectively, as a result of the absorptive influence of the subsoil. Applying the average annual outgo of 137 pounds of $MgCO_3$ and that of 101 pounds of $CaCO_3$ from the deep-tank control, the corresponding ratios of $MgCO_3$ to $CaCO_3$, on chemical equivalence basis, are 1:1.61, 1:1.52 and 1:1.99.

From 100-mesh magnesite. Each annual outgo of magnesium from the shallow tanks at the three rates was decidedly increased (about ninefold) where magnesite additions were made. The totals for the first 4 years were very close, 4331, 4265, and 4287 pounds, respectively, for the 8-, 32-, and 100-ton treatments, while the corresponding yields for the full 8-year period were 7670, 8146, and 7890 pounds. These results show the surface-soil outgo to be independent of increase in rates within these limits. Corrected for the average loss of 106 pounds from the control, the three magnesite additions yielded yearly averages of 853, 912, and 880 pounds.

Each of the twenty-four annual subsoil leachings contain a much larger amount of magnesium salts than the corresponding leaching from the surface soil. A part of each total surface outgo, however, passed through the subsoil. The three treatments showed average annual losses of 254, 339, and 319 pounds, in order, as against 137 pounds from the deep control, or actual treatment yields of 117, 202, and 182 pounds. The differences between the totals for each pair of shallow and deep tanks showed absorptions of 5539, 5438, and 5331 pounds, respectively. When compared with the stoppage exerted upon the leachings from MgO and $MgCO_3$, the results show that within so wide a range of concentrations of magnesium salts, there is both movement through and absorption by the subsoil. The extensive absorptions of 14,765 pounds from $MgCO_3$ at the 32-ton and 100-ton rates were nearly three times as great as the maximum of 5539 from the three magnesite treatments. Nevertheless, with this demonstrated absorption coefficient, considerable fractions of the magnesite-derived magnesium salts leached through the subsoil.

From 100-mesh wollastonite and serpentine. The calcium salts derived from the wallastonite in the surface zone displaced more magnesium from the subsoil than was contained in the leachings from the deep control tank. The magnesium outgo induced by the wollastonite was actually $1\frac{1}{2}$ times that which resulted from the magnesium silicate of the serpentine addition. The

increase in outgo of magnesium salts per annum from the serpentine addition was 50 pounds, which shows that with less concentrations of magnesium salts in the leachings, the subsoil permitted their downward movement, though the clay may be far from saturated. Based on the 8-year calculation from the 6-year outgo from the deep control, the calcium silicate of wollastonite caused an increased outgo of 1109 pounds $CaCO_3$-equivalent of magnesium salts through the subsoil, while the corresponding increase from the magnesium silicate of the serpentine treatment was only 405 pounds. Thus for each $CaCO_3$-equivalent pound of magnesium salts resulting from displacement by the calcium salts derived from the added calcium silicate, there was a direct yield of 0.365 pound from the added magnesium silicate. The lesser solubility of this particular serpentine, as compared with the readily hydrolyzed wollastonite, was established by carbonated water extractions. In this instance, however, the lesser solubility may be accentuated by a larger proportional absorption of the leachings from the serpentine, buffered by only about one-half as much of calcium salts as were present in the wollastonite leachings.

TOTAL CALCIUM-MAGNESIUM OUTGO FROM LIMESTONE AND DOLOMITE

The six limestone tanks and the six tanks containing dolomite afford opportunity for interesting comparisons as to the outgo of total calcium-magnesium salts. The limestone used is more soluble than the dolomite and of course has a much greater calcium-to-magnesium ratio. It will be remembered that the six materials other than dolomite show an enhanced outgo from the surface soil and absorption by the subsoil of the alkali-earth applied in excess. The subsoil absorption of a large part of the excess of outgo from surface treatment was followed by basic exchange in the subsoil. But in the case of the dolomite additions the subsoil effected removal of both calcium and magnesium from the drainage waters. The comparable surface-soil losses of 6889, 6641, and 6739 pounds from the 8-, 32-, and 100-ton treatments, respectively, of limestone resulted in comparable corresponding estopments of 4249, 4288, 4246 pounds when the leachings passed through the subsoil. The calcium outgo from both shallow and deep dolomite tanks, however, increased with increase in additions. The surface losses of 3589, 5248, and 5989 pounds from the three rates, in order, gave corresponding subsoil leachings, which carried 2266, 2636, and 2992 pounds. Since the preparation of this manuscript Morse (11) has made a contribution explanatory of the uniformity of outgo from the reserve fractions of the several limestone additions. The parallel of increase in additions and outgo may be accounted for possibly by the lesser solubility of the dolomite being offset by the greater surface afforded through increase in bulk of treatments.

The data of table 7 show the relationship between the total calcium-magnesium leachings from limestone and those from dolomite. The comparative uniformity of both calcium and magnesium outgo from the 3 limestone

additions in the shallow tanks is responsible for totals of 7583, 7527, and 7703 pounds, in order. This shows the outgo to be independent of the reserve stores of carbonate within the two extremes used. The average annual outgo of magnesium from the surface soil containing the three rates is 106 pounds, or exactly that from the shallow control. This demonstrates that no liberation of magnesium was brought about in the surface soil by the treatment. On the other hand, along with increase of calcium from the increase in dolomite additions, the surface soil gave a near-constant yield of magnesium. Because of the near-constant outgo of magnesium and the increase in losses of calcium, the dolomite showed total surface-soil losses of 6599, 8223, and 8856 pounds for the three additions, in ascending order. Thus, in the minimum treatment, the less soluble dolomite gave a surface-soil total outgo

TABLE 7

Total calcium-magnesium outgo from chemically equivalent amounts of 100-mesh limestone and dolomite in a loam soil—losses expressed as lbs. $CaCO_3$ per 2,000,000 lbs. of soil

	LIMESTONE			DOLOMITE		
	8 tons	32 tons	100 tons	8 tons	32 tons	100 tons
	lbs.	*lbs.*	*lbs.*	*lbs.*	*lbs.*	*lbs.*
From tanks without subsoil:						
Calcium	6889	6641	6739	3589	5248	5989
Magnesium	694	886	964	3010	2975	2867
Total	7583	7527	7703	6599	8223	8856
From tanks with subsoil:						
Calcium	2640	2353	2493	2266	2636	2992
Magnesium	2150	1991	2282	1999	2300	2195
Total	4790	4344	4775	4265	4936	5187
Stopped by subsoil	2793	3183	2928	2334	3287	3669

less than that from the more soluble limestone, but the reverse was true in the case of the 32-ton and 100-ton additions. Again in the case of the amounts of the two bases passing from the limestone treatments and through the subsoil, the losses appeared to be independent of rate of treatment, though replacement of magnesium in the subsoil was indicated in each instance. Hence, the subsoil yields of 2793, 3183, and 2928 pounds of total calcium-magnesium salts showed no relation to rate of treatment. But in the case of dolomite additions, the increases of calcium losses from the subsoil reflected the surface-soil parallel of increase in dolomite treatment and increase in calcium leachings. Therefore, as differing from the limestone outgo of total salts of calcium and magnesium through the subsoil, the dolomite totals from the subsoil increase with increase in additions. The average total leachings through the subsoil from the three additions of limestone and

dolomite were very close, 2141 pounds for the former and 2165 pounds for the latter.

SUMMARY

Calcium and magnesium leachings from 46 lysimeters over an 8-year period are reported. Treatments of CaO, MgO, $CaCO_3$, limestone, dolomite, and magnesite, in chemical equivalence, at three rates, were made to both deep and shallow tanks. Wollastonite and serpentine were also used in deep tanks. In summarizing, totals only are considered.

Increase in additions of CaO caused increases in outgo of calcium salts from both soil and soil-subsoil, and also increases in the amounts absorbed by the subsoil. Each lime addition caused depression in outgo of native magnesium from the surface soil and liberation of magnesium from the subsoil.

Each MgO treatment depressed the outgo of calcium from the surface soil and liberated from the subsoil more calcium than was leached from the corresponding $CaCO_3$ additions. The amounts of magnesium leached from the surface and the amounts stopped by the subsoil increased with rates of additions.

The outgo of calcium salts from $CaCO_3$ in the surface soil was found to be independent of the reserves of unabsorbed carbonate, for both shallow and deep tanks. Two of the three additions caused depressions in the outgo of magnesium from the surface soil, while all three caused augmented losses of magnesium from the subsoil.

All three $MgCO_3$ additions depressed the calcium outgo from the surface soil and accelerated that from the subsoil. With increased additions, there followed increases in outgo, with a maximum of 34,492 pounds, from the surface soil. The total amounts of magnesium absorbed by the subsoil were practically the same for the 32-ton and 100-ton additions, the two being about twice as great as the amount absorbed by the subsoil from the 8-ton addition.

In harmony with surface soil losses from the $CaCO_3$ additions, the leachings from 100-mesh limestone were practically the same for the three rates. The absorptions by the subsoil were also independent of rates of additions. The limestone additions showed either depression or but slight accelerations in the outgo of magnesium from the surface soil and liberations from the subsoil.

The losses of calcium from both shallow and deep dolomite tanks increased with increase in rate of treatment. The magnesium leachings, however, failed to show increase with increase in rate of additions. Differing from the other treatments, the dolomite leachings from the deep tanks showed increases of both absorption and passage for both calcium and magnesium.

All magnesite treatments showed a depressive effect upon the outgo of calcium from the surface soil and liberation from the subsoil, together with an augmented effect, independent of rate of addition, upon the magnesium yields from the subsoil.

Wollastonite materially increased the outgo of calcium from the surface soil and through the subsoil and increased the concentration of magnesium in the soil-subsoil leachings. Conversely, serpentine liberated calcium from the deep tank and increased the magnesium concentrations of the deep-tank leachings.

The control subsoil absorbed one-half of the calcium salts leached from the surface, which may account for the increase in its yield of magnesium salts.

Regardless of the concentrations of the several leachings when one base predominated, the subsoil absorbed a part of the content of the surface-soil leachings and permitted passage of concentrations of the predominant base in excess of those from the controls.

As a general tendency, it may be said that where additions gave a preponderance of one alkali-earth, the outgo of the other was depressed in the surface soil and accelerated in the subsoil; i.e., basic exchange was in effect in the subsoil, but "salting out" occurred in the surface soil.

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PARTIAL STERILIZATION OF SOIL, MICROBIOLOGICAL ACTIVITIES AND SOIL FERTILITY: III[1]

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The influence of partial sterilization upon the distribution and activities of microörganisms in the soil has been studied in the previous two papers (11, 12) of this series. It has been shown that partial sterilization depresses the fungi and protozoa and greatly stimulates the development of bacteria. This phenomenon is accompanied by an increase in the ammonia content of the soil, especially in soils rich in organic matter. It remains to be seen, however, how such a modified soil compares with the unmodified soil in its efficiency for decomposing organic substances added to it.

A uniform air-dry Sassafras soil, used in the previous experiments, was placed in 3-kgm. portions, in 6 pots and brought to optimum moisture. After three weeks' incubation, the pots were divided into three groups, two pots in each group. Group 1 was left untreated; 1 per cent of toluene was added to 2, allowed to act for three days, after which the soil was spread out to aid evaporation of the toluene; 0.5 per cent CaO was added to 3, and after 48 hours soil was spread for carbonation to take place. Numbers of microörganisms, nitrate and ammonia content were determined at various intervals, as shown in table 1.

Five days and 20 days after the evaporation of the toluene and carbonization of the CaO, several 100-gm. portions of the soils from the six pots were placed in tumblers and treated as follows: 0.25 gm. of dried blood was added to two tumblers in each group of pots, incubated for 2 weeks, and ammonia and nitrate determined; 30 mgm. of nitrogen as ammonium sulfate and 210 mgm. $CaCO_3$ were added to two other tumblers, which were then incubated 30 days and ammonia determined. These two methods for the study of nitrification in soil are discussed in detail elsewhere (10); 1 gm. of ground alfalfa meal was added to two other tumblers (containing 200 gm. of soil each) which were then placed in the respirator and the CO_2 evolution determined, as outlined in the previous papers; to two other tumblers in each group of pots, 0.5 gm. of finely cut filter paper was added, the mixture was incubated for 19–21 days and amount of cellulose decomposed determined.[2] The results are tabulated in tables 2–4.

The treatment of soil with toluene and CaO temporarily injured the nitrifying bacteria, as shown in table 2. This phenomenon has been repeatedly observed by other investigators. In the case of the control soil, 70 per cent

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[2] The authors are indebted to Mr. Heukalikian of this laboratory for making the cellulose determinations. The method used will be described in detail later.

TABLE 1

Influence of toluene and CaO upon the microörganisms and their activities in the soil

PERIOD OF INCUBATION	CONTROL POTS						TOLUENE TREATED POTS						CaO TREATED POTS					
	B + A*	A	F	Protozoa	NH_3-N	NO_3-N	B + A	A	F	Protozoa	NH_3-N	NO_3-N	B + A	A	F	Protozoa	NH_3-N	NO_3-N
days	*thousands*	*per cent of B + A*	*thousands*		*mgm.*	*mgm.*	*thousands*	*per cent of B + A*	*thousands*		*mgm.*	*mgm.*	*thousands*	*per cent of B + A*	*thousands*		*mgm.*	*mgm.*
Before treatment	11,900	17	40	C Fl	1.44	0.65	12,800	17	36	C Fl	1.44	0.82	14,200	20	42	C Fl	1.44	0.90
0	15,800	17	42	C Fl	1.54	0.70	6,300	13	0.33	0	2.28	0.78	8,960	5	14	C Fl	2.48	0.55
5	11,700	18	41	.....	0.74	2.30	5,400	9	0.33	.....	1.75	1.03	35,000	3	25	.....	1.68	0.53
15	9,400	23	28	C Am Fl	0.84	4.55	60,200	2	1.3	0	2.03	1.65	46,000	1	7.1	C Fl	1.47	0.54
23	10,600	23	25.3	C Am Fl	0.94	2.85	111,300	1	10.1	Am Fl	2.44	1.05	42,000	2	12.9	C Am Fl	1.42	0.70
40	11,070	20	18	.....	1.12	3.60	102,000	3	43.3	.....	4.18	1.10	70,000	1	9.3	.....	1.68	3.30
70	11,200	19	28.5	.....	1.44	4.55	38,000	6	49.2	.....	2.88	2.80	21,500	3	15	.....	2.02	4.95
90	10,150	25	24.5	C Am Fl	0.87	4.70	42,200	8	56	C Am Fl	2.31	4.05	18,000	3	7	C Am Fl	0.65	5.80

* B = bacteria, A = actinomycetes, F = fungi, C = ciliates, Am = amoebae, and Fl = flagellates.

of the soluble nitrogen, as a result of the decomposition of dried blood, was in the form of nitrate, while in the case of the toluene and CaO treated soil, there was no more nitrate than in the original soil, i.e., the dried blood had been transformed into ammonia, but none of this was nitrified. The same was true in the case of nitrification of the ammonium sulfate. The toluene treated soil was more efficient in decomposing dried blood than the CaO treated soil, but less efficient than the control soil. This was due to the difference in the active flora. The control soil, rich in fungi, decomposed the dried blood rapidly into ammonia and a part of the ammonia was oxidized into nitrates by the efficient nitrifying flora. In the toluene-treated soil, the fungi were supressed, while the bacterial flora was modified; the actinomycetes were, however, only slightly affected. As shown in the previous paper, actinomycetes can develop very rapidly in toluene-treated soils,

TABLE 2

*Nitrifying capacity of toluene and CaO treated soils**

AGE OF TREATED SOIL	TREATMENT OF SOIL	FROM DRIED BLOOD		$NO_3 - N$ FROM $(NH_4)_2SO_4 + CaCO_3$
		$NH_3 - N$	$NO_3 - N$	
days		*mgm.*	*mgm.*	*mgm.*
5	Control	7.8	18.7	30.9
5	Toluene	20.6	2.1	2.0
5	CaO	16.2	0.2	0.5
15	Control	5.4	23.2	
15	Toluene	20.8	2.3	
15	CaO		2.7	

* Incubation of tumblers: 14 days for dried blood, 30 days for the ammonium sulfate.

especially those rich in organic matter; this is the reason why the toluene-treated soil is less efficient in decomposing dried blood than the control soil but more efficient than the CaO treated soil. The bacterial numbers for the CaO treated soil were 35 millions in 5 days and 46 millions in 15 days, or 3–4 times as high as in the control soil; the actinomycetes, however, were depressed almost completely and the fungi to some extent. This soil with its high bacterial population was least capable of decomposing the dried blood. This was due, in addition to the relative inactivity of the fungi and actinomycetes, to the reaction of the soil which was pH 8+. A large bacterial population, therefore, may not necessarily indicate an active flora. This is brought out even with greater emphasis in tables 3 and 4.

When 0.5 per cent of alfalfa meal is added to the variously treated soils, different groups of organisms are stimulated. The fungi develop rapidly in the control soil, the bacteria and actinomycetes in the toluene-treated soil, and the bacteria in the CaO-treated soil. The results give a very interesting demonstration of the relative rôle of fungi, actinomycetes and bacteria in the decomposition of organic matter in the soil, as indicated by the evolution

of carbon dioxide. The control soil in which the fungi predominated was most efficient, the toluene-treated soil came next and finally the CaO-treated soil. The most efficient soil happened to be the one in which the bacterial population was least to start with, but which contained a vigorous fungous

TABLE 3

*Influence of alfalfa meal upon the microbiological activities in toluene and CaO treated soils**

AGE OF TREATED SOIL	TREATMENT OF SOIL	CO_2	NH_3†	NO_3	BACTERIA	ACTINOMYCETES	FUNGI	REACTION
days		*mgm.*	*mgm.*	*mgm.*	*thousands*	*thousands*	*thousands*	*pH*
5	Control	333.59	1.01	3.30	65,200	16,500	240	6.6
5	Toluene	292.98	2.95	0.35	181,000	50,000	169	6.8
5	CaO	273.28	1.01	3.60	224,000	5,500	137	7.6
15	Control	675.84						
15	Toluene	614.64						
15	CaO	608.00						

* For those soils which were analyzed 5 days after treatment 0.5 gm. of alfalfa meal was applied per 100 gm. of soil and incubated for 7 days; for the remainder 1 gm. of alfalfa meal was applied per 200 gm. of soil and incubated for 9 days.

† The amounts of ammonia and nitrate as well as numbers of microörganisms in the original treated soils, from which the samples of soil were taken for this experiment, are given in table 1 under the corresponding dates.

TABLE 4

*Cellulose-decomposing capacity of toluene and CaO treated soils**

AGE OF TREATED SOIL	TREATMENT OF SOIL	CELLULOSE DECOMPOSED	BACTERIA	ACTINOMYCETES
days		*per cent*	*thousands*	*thousands*
5	Control	38.4	25,000	1,200
5	Toluene	32.4	30,900	11,200
5	CaO	17.6	106,000	3,000
15	Control	59.4		
15	Toluene	50.8		
15	CaO	50.4		

* For each 100 gm. of soil 0.5 gm. of cellulose was used. The soils analyzed 5 days after treatment were incubated for 19 days; the remainder, 30 days.

flora. In the control soil the bacteria developed least and the fungi, most. In the toluene-treated soils, the bacteria developed to much larger numbers than in the control soil, but to a somewhat smaller extent than in the CaO-treated soil; fungi, however, developed to a more limited extent than in the control, although to a somewhat greater extent than in the CaO-treated soil; the actinomycetes developed most abundantly in the toluene-treated soil and it is these organisms which are partly responsible for the decomposition of

the organic matter in the toluene soil, above that of the CaO-treated soil. The natural conclusion from this experiment is that a large bacterial flora, when the fungi and actinomycetes are not considered, need not necessarily indicate a flora efficient in decomposing organic matter. As to the protozoa, they were present in great abundance in the control soil, entirely absent in the toluene-treated soil and present in limited numbers (chiefly flagellates) in the CaO-treated soil. No correlation whatsoever was found between the presence or absence of protozoa and the efficiency of a soil flora in decomposing organic matter.

Table 4 shows the efficiency of the flora in the three soils in decomposing cellulose, as indicated by the actual amount of cellulose which disappeared in the soil. The results for the soil used 5 days after treatment are more important, since the tumblers were incubated only 19 days. The samples taken 15 days after treatment, to which cellulose has been added were incubated for 30 days. The fungi developed at first abundantly in the tumblers containing the control soil, but not in the toluene- and CaO-treated soils. However, after a week or so, the soils became heavily reinoculated and all showed an equally abundant fungous flora. This accounts for the comparatively large amount of cellulose decomposed in the case of the soils taken 15 days after treatment, especially in the toluene- and CaO-treated soils. The same phenomena are brought to light here as in the case of the CO_2-evolution study. In the control soil, the bacteria developed to a limited extent, increasing from 11,700,000 to 25,000,000, the actinomycetes hardly developed at all, while the fungi increased in great abundance (to over 200,000 per gram). It is this soil which decomposed cellulose most efficiently. In the toluene-treated soil, the bacteria increased from 5,400,000 to 30,900,000, while the actinomycetes increased to 10 times the number of the control soil; the fungi were low at first, but, due to the long period of incubation, they also finally increased to large numbers. In the CaO-treated soil, the bacteria have reached the highest numbers, while the actinomycetes increased slowly and the fungi only at the latter part of the incubation period. It is not so much the high number of bacteria which is responsible for the decomposition of cellulose in the soil as the high number of fungi and actinomycetes.

It remains to be seen how the various organisms developing in the soil can be made to liberate the nitrogen that they have assimilated in their bodies.

Störmer (8), Stoklasa (7) and others have claimed that the stimulating action of the disinfectants upon bacterial activities and ammonia accumulation is due to the destruction of large soil organisms, such as worms, insects, nematodes, algae, fungi, protozoa as well as bacteria; these are then decomposed by the surviving bacteria with the result that a rapid bacterial development takes place accompanied by an abundant ammonia formation. As a matter of fact, Störmer suggested that, since the total increase in ammonia nitrogen in the treated over the untreated soil is not more than 3–4 mgm.

of nitrogen per 100 gm. of soil, this quantity can readily be derived from the decomposed organisms. Hiltner (4) used a logical process of reasoning in demonstrating the destruction of fungi and actinomycetes by volatile antiseptics. When straw is added to the soil, the available nitrogen is stored away by the microörganisms to the detriment of the higher plants. When the soil is treated with CS_2 during or after the addition of straw, the injurious influence is not observed. This was explained by the fact that, in the case of straw fertilization, the soil nitrogen is stored away chiefly by fungi and actinomycetes. The disinfectant, in destroying the fungi and actinomycetes, prevents the storing away of the soil nitrogen, which thus becomes available for higher plants. These considerations were based merely on theoretical considerations. No actual facts have been submitted to demonstrate whether they are true or not. According to this theory, the stimulating effect of disinfectants and heat upon bacterial development is due to the destruction of protozoa, with the result that their dead cells serve as an available source of energy for the bacteria, while according to the protozoan theory the beneficial influence of disinfectants is due to the destruction of protozoa which otherwise check the development of bacteria.

The results that we have previously reported have shown that there is no correlation (except in one or two instances) between the suppression and later development of protozoa and bacterial development. There is, however, a certain correlation between the development of bacteria and of filamentous fungi in the soil. The authors do not claim that the development of fungi in the soil has a depressive action upon the development of bacteria, but merely that the numbers of bacteria are governed by the balance of microörganisms in the soil, including the fungi and actinomycetes and perhaps also the protozoa. If the assumption of Störmer (8), Stoklasa (7) and others could actually be demonstrated, namely that the influence of disinfectants in destroying a large part of the microbial population of the soil makes their bodies available as a source of energy for the bacteria, it would throw a great deal of light upon the subject under consideration. Not that it would solve the problem, but it would be merely one more link in the chain explaining the very complex phenomenon resulting from the partial sterilization of soil. To demonstrate the rôle of disinfectants in the making of dead bodies of soil microörganisms readily available sources of energy for bacteria, those microörganisms would have to be introduced in sufficient quantities in the soil, so as to allow measurable increases in bacterial development to take place and yield measurable quantities of ammonia. Were these added in the form of fully developed cells grown on artificial culture media, a good deal of the material might consist of dead autolized cells rich in proteins and minerals, or nutrients adhering from the artificial medium; this would have created purely artificial conditions. The problem is to bring about a rapid increase of one or more groups of microörganisms in the soil, without modifying the physical and otherwise microbiological condition of the soil and especially without de-

stroying, injuring or otherwise modifying the activities of protozoa and without adding fresh protein material to the soil. The filamentous fungi were selected as a group of organisms to be stimulated, for various reasons:

1. We know more about the specific metabolism of these organisms than about many other soil microörganisms. 2. They grow rapidly. 3. Methods have been developed (9) for at least an approximate determination of their abundance in the soil. 4. Our previous results have shown us that the abundance of fungi in the soil is appreciably affected by treatment of soil with disinfectants. 5. They do not enter into the system "protozoa-bacteria" as developed by Russell and associates. 6. They can be handled, studied, identified in the laboratory and controlled in the soil more readily than worms, nematodes, insects, algae and protozoa.

Studies now being carried on in our laboratory and the data reported previously by other investigators on the influence of cellulose upon the activities of soil microörganisms as well as on the specific groups of organisms concerned in the decomposition of cellulose in the soil, demonstrated that the addition of pure cellulose to the soil greatly stimulates the development of fungi and that the fungi use up all the available nitrogen compounds in the soil, in the presence of sufficient cellulose as a source of energy, and convert it into fungus protoplasm. The growth of fungi may be so abundant as a result of addition of cellulose to the soil, especially if the soil is rich in nitrates, ammonium salts and other available nitrogen compounds, that it is difficult to accurately count the numbers of bacteria and actinomycetes by the common plate method using synthetic media. This may even be the case with high dilutions. As a result of adding cellulose to ordinary soil, the bacteria and especially the actinomycetes are also stimulated but to a lesser extent than the fungi.

This phenomenon has been utilized for increasing the fungus content of the soil. The cellulose used was pure, ash-free filter paper, cut up into very small pieces and well mixed with the soil. Four 1-kgm. portions of the same air-dry soil used in the previous experiments were placed in 4 glazed earthenware pots and the optimum amount of moisture added (20 per cent). One per cent of cellulose was well mixed in with the soil in two of the pots before the moisture was added. The pots were covered with glass plates and placed in the incubator. No nitrates or nitrogen salts were added, since it was known from previous work with the particular soil that nitrates will accumulate very rapidly when the soil is kept under optimum moisture and temperature conditions. However, since all the nitrate had disappeared in the cellulose pots after 8 days' incubation (see table 5), 500 mgm. of $NaNO_3$ (82 mgm. N) was added on the twentieth day of incubation to each of the four pots so as to allow as complete a transformation of the cellulose into fungus mycelium as possible. The addition of a large amount of nitrate to the cellulose-free soils, already rich in nitrate led to a partial reduction of the nitrate to ammonia; in the cellulose pots, however, no such reduction took place. Twenty days after the addition of nitrate, the soils from the four pots were transferred to glass stoppered bottles, 2 per cent of toluene was

added to each and allowed to act for 72 hours. At the end of that period of time, the soils were spread out for the toluene to evaporate and returned to the original pots, brought up to moisture, covered and placed in the incubator. Determinations of numbers of microörganisms, ammonia and nitrate content are shown in table 5.

Treatment of the soils with toluene brought about first a decrease, then a decided increase in the number of bacteria both in the soil to which no cellulose has previously been added and to the cellulose-treated soils, the increase

TABLE 5

Influence of cellulose upon the growth and activities of microörganisms in the soil

PERIOD OF INCUBATION	NO CELLULOSE ADDED TO SOIL						1 PER CENT OF CELLULOSE ADDED TO SOIL					
	B + A per gm. soil*	A	Fungi per gm. soil	N per 100 gm. soil			B + A per gm. soil	A	Fungi per gm. soil	N per 100 gm. soil		
				as NH_3	as NO_3	Total				as NH_3	as NO_3	Total
days	*thousands*	*per cent of B+A*	*thousands*	*mgm.*	*mgm.*	*mgm.*	*thousands*	*per cent of B+A*	*thousands*	*mgm.*	*mgm.*	*mgm.*
8†	33,800	10.0	48.0	.....	10.8	.....	41,400	9	458	....	Trace	0
34	19,000	16.0	49.5	8.69	17.8	26.49	40,000	?	1315	1.80	6.1	7.90
43	16,400	22.0	12.0	8.30	17.9	26.20	22,200	39	63	2.30	8.8	11.10
52	25,400	8.7	13.5	9.71	17.2	26.91	64,700	5	140	6.84	4.5	11.34
69	62,500	7.0	17.5	11.52	18.2	29.72	95,500	16	162	9.36	3.9	13.26
98	46,500	6.0	142.0	12.67	15.7	28.37	78,500	15	197	7.75	8.8	16.55
118	38,000	7.0	33.0	11.52	15.8	27.32	77,000	20	225	0.95	15.5	16.45

* In this table, the term "Soil" means moist soil just as it was removed from the culture pots.

† Treatments consisted of mixing 1 per cent of cellulose with dry soil and adding 20 per cent of water just before the period of incubation. After 20 days of incubation 82 mgm. of nitrate nitrogen was added to the soil in each pot. Twenty days after the addition of the nitrate, the soils were treated with toluene which was evaporated three days later.

being greater in the case of the latter. The fungi were reduced by the use of toluene and then increased greatly, more so in the cellulose treated soils. The total soluble nitrogen increased only slightly in the soils to which no cellulose has been added, while in the cellulose-treated soils there was a steady increase; in 78 days after toluene-treatment the soluble nitrogen in the former increased from 26.49 to 27.32 mgm. per 100 gm. of soil while, in the cellulose-treated soils, it increased from 7.90 to 16.45 mgm. This is due to the gradual decomposition of the fungi and other microörganisms which have originally stored away the nitrate in the form of microbial proteins using the cellulose as a source of energy.

DISCUSSION

To be able to understand the change in the growth and activities of the different groups of microörganisms in the soil, as a result of partial steriliza-

tion, we must clearly understand the differences in the metabolism of these groups of microörganisms, especially the nitrogen and carbon (energy) metabolism; we must also in some cases diffierentiate between the amount of carbon used by the organisms for structural and functional purposes and the amount of nitrogen needed for synthesis of microbial protoplasm and liberated as a waste product in the form of ammonia. In other words, the carbon and nitrogen of each representative group of soil organisms should be kept in mind when we attempt to understand and interpret the changes in the carbon and nitrogen cycles in the soil.

The three groups of soil microörganisms, which take an active part in the transformation of carbon and nitrogen in the soil are the fungi, actinomycetes, and bacteria. These are the organisms that develop on the plates and which we are thus able to count. There are other microörganisms in the soil which undoubtedly take an active part in the carbon and nitrogen cycles, especially the protozoa, and possibly the nematodes, rotifers and worms. By consuming living microörganisms or dead organic matter, the latter bring about certain changes in the chemical condition of the carbon and nitrogen in the soil. However, our knowledge on the metabolism of these organisms in the soil is still insufficient to warrant any generalizations. What we do know leads us to think that there is at least no appreciable increase or decrease in the total amount of carbon and nitrogen in the soil, as a result of their activities, although there may be a change in the physical and chemical condition of the soil. The algae may also take a part in increasing the carbon and nitrogen content of the soil, but their contribution to the chemical changes in the soil is still not definitely known. Still less do we know about the activities of the ultra microscopic and filterable organisms that no doubt exist in the soil.

It remains, therefore, for us to keep in mind the metabolism of the fungi, actinomycetes and bacteria—the three leading groups of microörganisms which take an active part in the transformations of carbon and nitrogen in the soil. Out of these three groups, the metabolism of the bacteria is the most complex, since it differs with the different representatives of the group. Those bacteria that develop on the plate are heterotrophic forms, so that the important nitrifying, sulfur oxidizing and other autotrophic bacteria are left out; conditions are aerobic, so that the obligate anaerobes are left out; most of the nitrogen-fixing organisms and probably many cellulose decomposing forms as well as others do not appear. But even the heterotrophic forms developing on the plate can be readily divided into two distinct groups: the spore forming and the non-spore forming types. The former grow rapidly, are usually strongly proteolytic, decompose readily starches and other carbohydrates. The non-spore forming bacteria grow slowly, either liquefy gelatin or do not liquefy it at all, and do not attack starches and other carbohydrates readily. Of the colonies developing on the plate, outside of the fungi, the actinomycetes occupy 15 to 35 per cent, the spore-forming bacteria 5–10 per cent and the non-spore forming bacteria 55–70 per cent. There is evi-

dence to believe [Conn (1, 2)] that of the two groups of bacteria, the non-spore forming group is not only the most predominant but the most active in the soil. Of special interest is the energy metabolism of these organisms; they seem to use proteins much more readily than carbohydrates(?), thus liberating comparatively large quantities of ammonia. It is, therefore, quite natural that the great majority of media recommended for the cultivation of bacteria should contain a protein in one form or another, while in the case of fungi and actinomycetes, a carbohydrate is usually offered as a source of energy. The following paragraphs deal with the carbon and nitrogen metabolism of the organisms developing on the plate.

Fungi

Fungi prefer carbohydrates as sources of energy although they can also use proteins; of the carbohydrates, many can utilize celluloses, hemicelluloses and starches, others only the derivatives of those products. Nitrogen can be obtained from nitrates, ammonium salts, amino acids and proteins. They grow rapidly and may use up to 50 per cent of the carbon assimilated for the synthesis of their protoplasm. Although the nitrogen content of fungus mycelium varies within 3.5 to 7.0 per cent, large quantities of nitrogen will be transformed into fungus protein due to the abundant assimilation of carbon. When an organic substance containing a small amount of nitrogen (less than 1.5 per cent) is acted upon by fungi, the organisms may decompose it very rapidly, liberating large amounts of CO_2, but, in view of the large amount of carbon assimilated, an additional source of nitrogen will be required; this additional need for nitrogen increases with a decrease in the nitrogen content of the energy bearing material.

Partial sterilization of soil practically eliminates certain groups of fungi from the soil and greatly reduces the number of all fungi. It requires some time, depending upon treatment and content of organic matter in the soil, before the fungi become reëstablished. Their rapid multiplication then depends upon the amount of energy available. If that is at all extensive, the fungi multiply rapidly, especially when reinoculated. Their rapid development will result in two phenomena: (a) a competition with the heterotrophic bacteria for the available energy, which will lead to a diminution of the latter and (b) a stop to a further increase of the soluble nitrogen in the soil. This action of fungi upon bacterial multiplication and activities is indicated by a number of statements in the literature, of which we need only cite that of Scherpe (6).

Scherpe (6) found in 1909 that the treatment of soil with CS_2 decidedly stimulated the development of fungi, which influences the nitrogen transformation in the soil by fixing in the mycelium the easily assimilable nitrogen compounds in the soil or the ammonia liberated by the bacteria. Scherpe, therefore, suggested that fungi may play an active part in the group of phenomena resulting from treatment of soil with CS_2. It is important to note that

some fungi actually secrete substances toxic to the development of bacteria, as shown by Nadson and Zolkiewicz (5) for *Spicaria* and as observed repeatedly by the authors in the case of certain species of *Rhizopus*, whose development on the plate is sufficient to repress almost completely the development of the bacteria.

Actinomycetes

Actinomycetes are not any more appreciably affected by partial sterilization than the bacteria developing on the plate. In other words the ratio of actinomycetes to the total number of bacteria developing on the plate may remain the same, may slightly diminish or may even increase, as a result of partial sterilization. While the fungi are practically eliminated, the actinomycetes are diminished only slightly in numbers. However, their multiplication is very slow and when the bacteria begin to multiply rapidly as a result of partial sterilization, the numbers of actinomycetes may remain stationary, while their ratio rapidly diminishes, in proportion to the increase in bacterial numbers. When available energy like cellulose is added, the actinomycetes begin to multiply rapidly. They can use as sources of energy celluloses and other carbohydrates as well as proteins. Ammonium salts, nitrates, amino acids and proteins can be used as nitrogen sources. In their carbon-nitrogen metabolism they stand between the aerobic bacteria and the fungi, having a higher nitrogen content than fungi and making a much less abundant growth. Their activities would tend to bring about an increase in the available nitrogen in the soil rather than a decrease, unless an excess of energy material, free from nitrogen, is available. These organisms will therefore consume a smaller amount of nitrogen with the same amount of cellulose decomposed; they will liberate a greater amount of ammonia from proteins than fungi, for the same amount of protein decomposed.

The development of actinomycetes probably does not act as a direct repressive agent of bacteria even though the ratio of actinomycetes increases when the bacteria begin to diminish. The latter may possibly be due not so much to a direct increase of numbers of actinomycetes, but to a relatively greater decrease of bacteria.

Treatment of certain soils with toluene or CS_2 may make them more favorable media for the development of actinomycetes, as shown in the previous papers (11, 12).

Certain actinomycetes produce substances toxic to bacteria, as shown by Greig-Smith (3) and as often observed in our own work, when around an actinomyces colony upon a plate, a zone is found free from fungus and bacterial growth.

Spore-bearing aerobic bacteria

These organisms decompose chiefly soil proteins, starches and simpler carbohydrates. One or two species of the anaerobic forms can also decom-

pose celluloses. These organisms make a more limited amount of growth than the fungi and actinomycetes, but their bodies are richer in nitrogen, containing 6 to 12 per cent (usually 10 per cent) of this element. In other words, the nitrogen content of bacteria is twice as high as that of fungi. They are also less economical in their utilization of carbon than fungi.

Non-spore bearing bacteria

These organisms readily utilize proteins and other carbon-nitrogen compounds as sources of energy. Some can also decompose celluloses and other carbohydrates. A great many of these organisms (developing on the common plate) thrive, however, with celluloses, starches and other carbohydrates as sources of energy to a lesser extent than the spore-bearing bacteria and much less so than the fungi and actinomycetes. Their nitrogen content is about 10 per cent, while they utilize carbon even less economically than the spore-bearing bacteria. It is this group which contains the majority of organisms developing on the plate and it is this group which is favorably affected by partial sterilization of soil.

When soil is treated with heat and antiseptics, the organic matter is modified and made more readily available. The fungi are destroyed. The nematodes, protozoa, insects, worms are also destroyed and leave an abundant supply of relatively available material. The non-spore bearing bacteria are the first to become active and to multiply rapidly. Masses of these organisms are easily broken down in preparing the soil dilution and show up readily on the plate. They decompose proteins and other nitrogenous substances readily as a source of carbon. Only a small amount of the carbon is assimilated and converted into microbial proteins, and *ipse facto* only a small amount of the nitrogen is assimilated. Most of the carbon is liberated as CO_2 and the nitrogen as ammonia; in the absence of nitrifying bacteria, the latter is left in the soil as such. When the partially sterilized soil is reinoculated with fresh soil, various other organisms, and particularly the fungi are reintroduced. These organisms find the treated soil a favorable medium for their development.

Our knowledge of the kinds and activities of soil microörganisms is still insufficient; we know very little about the various antagonistic and associative influences between the various groups of soil microörganisms, especially between the bacteria on the one hand and actinomycetes, fungi and protozoa of the other. It is not a question of one group of organisms destroying another group, although this may take place under exceptional circumstances, but it is chiefly a question of competition for available nutrients especially energy, or of one group developing more readily in the absence of the other groups. Under normal conditions very little readily available nutrients, especially energy sources, are present in the soil at any one time. The introduction

of available energy combined with nitrogen and minerals, as in the case of alfalfa hay, brings about a stimulus to microbial activities similar to partial sterilization. Some microörganisms liberate available nitrogen compounds in the soil, others transform them into microbial protein, in the presence of available energy; a certain balance or equilibrium is established between these phenomena in ordinary soils. Partial sterilization changes this equilibrium.

The effect of partial sterilization of soil is a resultant of the sum total of the changes in the physical and chemical condition of the soil on the one hand and of the modification of the biological flora on the other. Treatment with antiseptics, heat, calcium oxide, air drying etc. affect the first and modify the second and the resultant phenomenon is an increase in the number of bacteria and ammonia content of the soil.

SUMMARY

1. Partial sterilization of soil brings about a chemical change in the organic matter of the soil, making it more available as a source of energy for microorganisms. This is indicated by (a) the ammonia formation (even if only a small amount) in the process of sterilizing the soil by heat or disinfectants; (b) by the fact that the curve of CO_2-evolution in partially sterilized soil is similar to that obtained when a small amount of undecomposed organic matter is added to unsterilized soil; (c) by the fact that soils rich in organic matter allow a greater accumulation of ammonia and nitrates, as a result of partial sterilization, than soils poor in organic matter, independent of the flora and fauna; (d) partially sterilized soil with a much greater bacterial flora is no more efficient in decomposing nitrogenous and non-nitrogenous organic substances added to it.

2. A large proportion of the soil fungi are killed as a result of partial sterilization. This dead material with the bodies of destroyed protozoa and other soil microörganisms still further increases the amount of energy made available in the soil.

3. The rapid increase in the numbers of microörganisms in the soil is at the expense of the organic matter made available. This is further confirmed by the fact that the course of development of fungi results in a curve somewhat similar to that given by the bacteria, although the rise in the curve may take place at a later date. The numbers of fungi, however, may not indicate the period of maximum activity which may have been passed already. Large numbers of fungi, shown by the plate method, may be due to abundance of spores. Where active growth of fungi takes place, due to available nutrients, spore formation may be greatly delayed. The vegetative mycelium, however extensive, may show much smaller numbers than when spore formation occurs.

4. The carbon and nitrogen are present in the soil in a certain proportion, depending upon the physical and chemical condition of the soil; when the

carbon compounds are decomposed as sources of energy by the bacteria and actinomycetes some of the nitrogen is left as a waste product. The carbon-nitrogen content of the soil and of the bodies of the bacteria, actinomycetes and fungi combined with the economic utilization of the carbon by these three groups of organisms, explain why the development of the first two groups of organisms will bring about the liberation of nitrogen from the soil organic matter to a greater extent than the development of the fungi.

5. The actual amount of ammonia formed in partially sterilized soil is determined not by the numbers of bacteria and fungi developing in the soil but by the abundance of organic matter. The course of development of numbers of bacteria in the soil seems to be influenced by the course of development of the fungi. The course of development of actinomycetes depends upon the method used in bringing about the partial sterilization of the soil as well as by the organic matter content of the soil.

6. The protozoa are suppressed in partially sterilized soil, but become active again long before the bacterial numbers drop down very markedly.

7. The more rapid the rise in bacterial numbers and the greater the maximum, the sooner will the fall set in. This is exactly true of the numbers of fungi. These phenomena are results of the amount of available plant food in the soil.

8. The phenomena observed as a result of partial sterilization of soil, namely the rise of bacterial numbers and ammonia accumulation are explained by (a) the change in the physical condition of the soil, especially the soil colloids; (b) the change in chemical condition, especially modification of soil organic matter, making it more readily available; (c) the destruction of a large number of soil microörganisms, especially the fungi and protozoa, making their bodies available as sources of energy for the surviving microörganisms; (d) the change in balance of the microbiological flora of the soil (all of these favor greatly the development of the bacteria); and (e) the fact that bacteria use organic nitrogenous substances (as well as other carbon compounds) very uneconomically as sources of energy and liberate a great deal of ammonia as well as phosphates and other minerals stored away in the soil organic matter as waste products.

9. These results apply to normal soils. It is possible that under certain conditions other phenomena become controlling factors. We need only mention soils infested with fungi causing plant diseases or sewage farming and greenhouse soils, where protozoa may become controlling factors.

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CONVENIENT SUPPORTS FOR PLANTS IN POT OR WATER CULTURE EXPERIMENTS

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It is frequently necessary to provide some means for supporting plants that are to be grown for some time in either pot or water culture experiments. It is desirable that such supports be light, substantial, easily attached and interfere as little as possible in handling the pots. For our own convenience two methods have been devised. Plate 1 shows each of the two methods described. The sticks on the jar on the left are inserted into metal sockets each made from a piece of galvanized sheet iron two inches square. These are made by hand as indicated in figure 1.

The middle jar in plate 1 shows plants during their growth in water cultures; the pot on the right shows the perforated earthenware cover which holds the plants and the wood supports. The cover fits over the mouth of the one-gallon earthenware jar and the plants are held at the proper place in the cover by means of plugs of cotton. The roots are submerged in the nutrient solution contained in the jar. This arrangement makes it easy to lift off the cover carrying the plants when changing the culture solution. Three of the four holes for the wood supports are shown in the outer edge of the cover. The holes within the rim are about $\frac{1}{4}$ inch in diameter.

The earthenware covers were made for us by the Maurice A. Knight Company and have proved to be very satisfactory for growing plants in water cultures. Similar covers made of wood and water-proofed with paraffin proved to be unsatisfactory because of their lightness, warping, cracking and affording a foot-hold for the growth of molds. The earthenware cover eliminates these troubles.

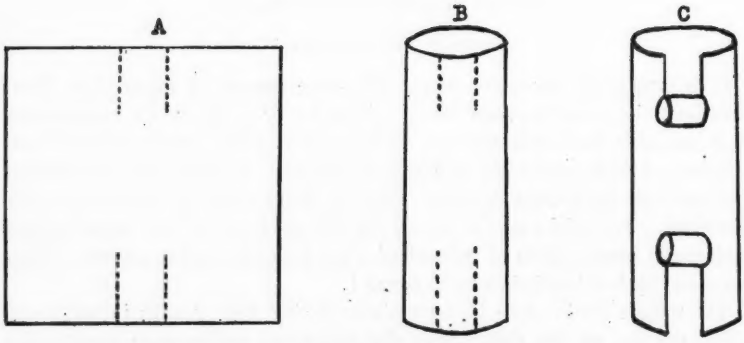
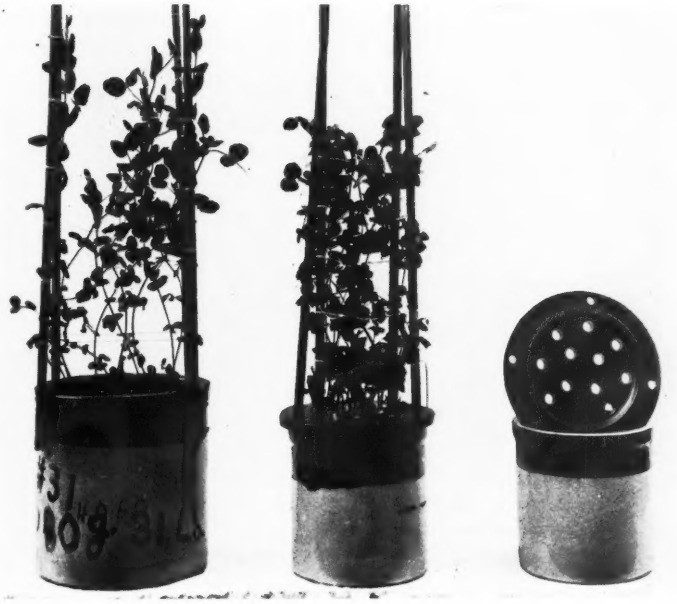


FIG. 1. METHOD OF MAKING METAL SOCKETS FOR PROPS

At A the metal square has been cut along the dotted lines, and at B the square has been bent into the form of a cylinder. This is done by bending one edge over the other and hammering over an iron rod about ½ inch in diameter until a cylinder is formed. At C the small tongues have been bent over a no. 4 nail with a pair of pliers. Four of the sockets are then strung on two pieces of baling wire at equal distances apart on the wires and attached to the top of the jar by twisting the ends of the same piece of wire together around the jar until tight. Rods of wood are placed in the metal sockets and twine stretched from one support to another at the proper height, as may be needed during the growth of the plants to keep them in an upright position.



A NEW APPARATUS FOR MECHANICAL ANALYSIS OF SOILS

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The study of soil physics, very popular some years ago, seems to be reviving. Chemical and bacteriological studies of soils have not given entirely satisfactory explanations of the various factors which affect soil fertility. The advance of physical chemistry has added many new methods and implements to be used in this work and is giving a greater insight into the phenomena that must be investigated.

The author wishes to present a preliminary description of an apparatus devised for obtaining a better conception of the physical constitutents of the soil. It has always been recognized that the proportions of the soil particles of various sizes were the controlling factors in determining soil characteristics and various means of making mechanical analyses have been devised for determining these proportions.

For some time these methods have been recognized as inadequate in that they do not give a sufficiently detailed picture of the soils. The separation, which is necessary, into fractions of arbitrarily fixed diameters is not satisfactory because the soil is made up of particles varying in size continuously and not by steps. The picture presented by such an analysis is not correct.

Recently Sven Oden (1) has described an apparatus which much more nearly indicates the actual mechanical composition of the soil. By suspending the soil particles in water and allowing them to settle upon the pan of a balance, recording automatically the time required for a definite weight of particles to settle, he obtains by mathematical calculations a distribution curve.

The apparatus here described is patterned somewhat after Oden's balance. It goes farther than his, however, in that it draws the distribution curve itself, thereby eliminating the complicated calculations necessary with Oden's balance. The illustration shows the balance diagramatically. The instrument as now made has not as yet been corrected or even calibrated. It is not the intention of the author that it should be constructed as delicately as Oden's apparatus since it does not seem probable that very minor differences in texture are of significance in soils. The apparatus has been tested only experimentally as yet. It has been found that some features should be changed. It seems particularly necessary that the recording drum revolve much faster. The balance may need to be made somewhat more sensitive in order than smaller quantities of soil may be used.

The principal feature of the apparatus is the recording arrangement. If the balance beam recorded its movements by marking upon the moving chart, the necessary friction would reduce its sensitivity. This was avoided by making the record electrically. A momentary contact at regular intervals causes a spark to jump from the point at the end of the beam to the revolving cylinder, passing through the record chart and burning a small hole. Since the electrical connection is made at the base of the balance column and the current carried up that through the torsion spring to the beam, all friction due to recording is eliminated from the beam.

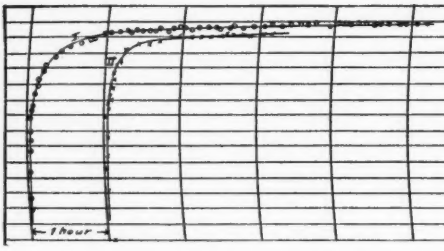

FIG. 1. CURVES SHOWING ACTUAL POINTS AS LOCATED BY BALANCE

I. Deflocculated
II. Not deflocculated

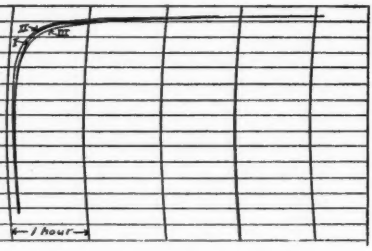

FIG. 2. CURVES OF THREE SOILS NOT DEFLOCCULATED

I. Webster silty clay loam
II. Carrington loam
III. Lintonia silt loam

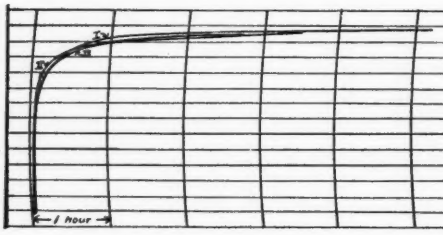

FIG. 3. CURVES OF THREE SOILS DEFLOCCULATED

I. Webster silty clay loam
II. Carrington loam
III. Lintonia silt loam

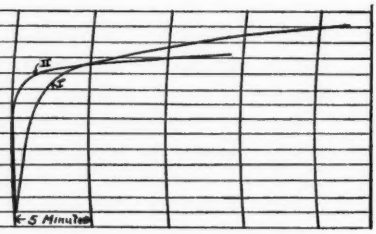

FIG. 4. CURVES OF TWO SOILS DRAWN AS THOUGH RECORDING MECHANISM WERE REVOLVING TWELVE TIMES AS FAST

I. Webster silty clay loam
II. Carrington loam

The wiring diagram explains the electrical system of the recording mechanism. In order to obtain momentary electrical contacts for the sparks at regular intervals a mechanism of which a description has been published (2) was utilized. Switch *A* in the diagram was installed to give contacts other than the automatic ones whenever wanted. During the first five minutes

of the determination, the coarser particles settle so rapidly that more frequent contacts are necessary in order to secure the first part of the curve.

Figures 1–4 show curves obtained by the apparatus. These do not represent the entire soil, but only that portion consisting of very fine sand silt and clay from which the coarser particles have been sifted out. Seven-gram sam-

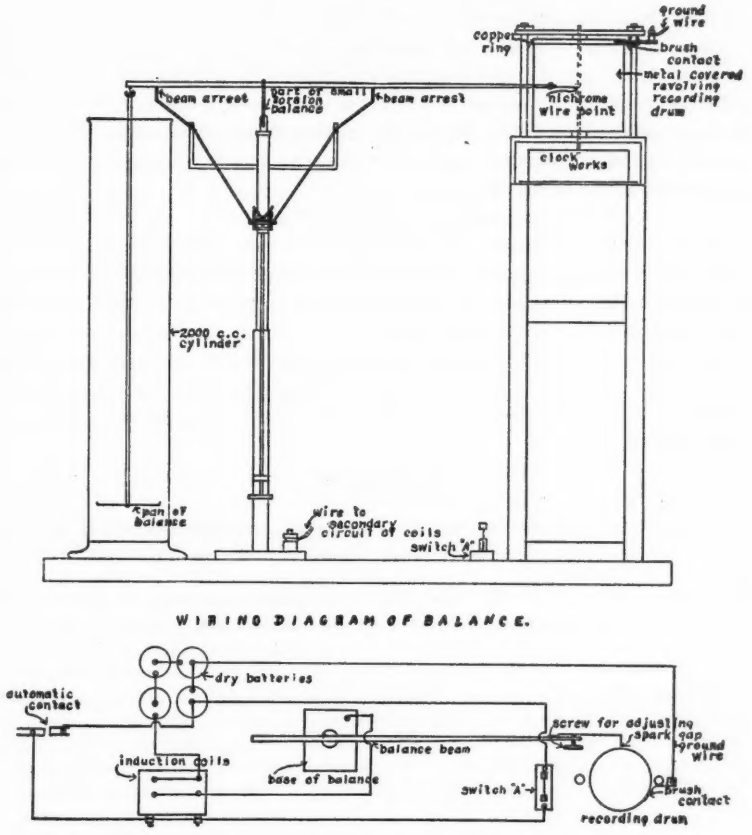

FIG. 5. AUTOMATIC RECORDING BALANCE ARRANGED FOR MAKING MECHANICAL ANALYSES OF SOILS

ples of the fine material were used. Since the balance pan was only two and one-half inches in diameter while the cylinder was three and one-fourth inches in diameter, only a little over four grams of soil would fall on the pan.

Figure 1 shows the points actually recorded by the apparatus. The points are not exactly on the line because of the fact that the spark does not always jump from the point perpendicularly to the cylinder. However the points

are sufficiently numerous to allow the drawing of curves as in this figure. Figures 2 and 3 give curves for three soils. In figure 2 the soils were shaken in distilled water for six hours and in figure 3, a few drops of ammonium hydrate were added to the distilled water and soil and solution shaken for six hours. The time of shaking was chosen arbitrarily because these were just trial runs. The recording drum made one revolution in twelve hours. In figure 4 the curves for two of the soils shown in figure 3 were reproduced by dividers so as to represent the recording cylinder as revolving twelve times as fast. In figures 2 and 3 all three soils appear similar but in figure 4 the differences are quite marked, because the chart is represented as having revolved twelve times as far during the intervals between sparks. If the recording cylinder made a revolution once an hour it is evident that the soil differences would be clearly shown.

In order to make a complete mechanical analysis a sulfur photometer could be used to determine the turbidity of the suspension after two hours settling. The clay content could be estimated by calibrating the photometer to indicate the amounts. A photometer has been used in some turbidity determinations here with good results.

This article is presented merely as a preliminary report that may lead others to further work along this line. It is hoped that the apparatus herein described may be perfected soon so as to be a very practical aid in soil investigations.

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A COMPARISON OF SAND AND SOLUTION CULTURES WITH SOILS AS MEDIA FOR PLANT GROWTH

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Several years ago, one of the writers (13) described certain experiments on the growth of barley plants in sand and solution cultures, and a number of general questions were raised pertaining to the interpretation of results obtained by the use of these methods. The experiments have been continued and it is now possible to extend the previous discussion. This appears to be the more desirable because of the wide application which is now being made of sand and solution cultures by plant physiologists and by investigators in agricultural experiment stations. It seems appropriate at the present time to inquire further into the possibilities and limitations of these methods. What factors are left uncontrolled in such experiments? What are the points of similarity or dissimilarity between solution, sand, and soil cultures? These and questions of like nature must be of interest to all who are concerned with the interrelations of plants and essential inorganic elements. It is our purpose in the present paper to invite a critical consideration of these questions and to offer some experimental data which seem to have a direct bearing on them.

Recently Davis (9) published an account of a comprehensive series of experiments carried on in this laboratory with wheat plants for the purpose of determining the influence of variability on the interpretation of data obtained from solution cultures. While the importance of the variability factor has long been recognized by biologists, its significance to plant-culture experimentation had been quite generally overlooked. The work of Davis makes it certain that small differences in dry weights of plants grown in solutions of slightly varying composition may have no meaning when the data are interpreted with regard to the probable error. In fact, at certain seasons of the year, Davis has found more recently (data not yet published) that the "best" and "poorest" solutions of the Shive series produced the same yields of wheat plants. These findings obviously point to the necessity for disregarding any differences of small magnitude in ordinary experimentation with a limited number of plants.

EFFECT OF DIFFERENT VOLUMES OF CULTURE SOLUTION ON PLANT GROWTH

In the previous article the writer emphasized (not, of course, for the first time) another factor which seems to have an important bearing on the interpretation of solution culture data. This is the change which takes place in the composition and concentration of a culture solution as a result of the absorption of ions by the plants. Under some circumstances, such changes

may be extremely rapid. Naturally the rate of change will depend upon the volume of solution provided for each plant, upon the concentration of the solution and upon the size and rate of growth of the plant. It should, therefore, be possible to obtain different results with the same solution simply by varying the size of the containers and the number of plants grown in each container.

An experiment was carried out to illustrate this point. Barley plants were grown for six weeks under the following conditions:

1. Regular culture solution, one plant in two liters, solution changed twice each week.
2. Dilute culture solution, one plant in two liters, solution changed three times each week.
3. Dilute culture solution, six plants in one liter, solution changed twice each week.

This simple experiment showed very clearly (table 1) that the same dilute solution may produce plants of very different sizes, depending upon the size of the containers and the number of plants grown in each container. By analyses of the residual solutions, it was shown that with treatment 1 the concentrations of the various ions were maintained at an approximately constant value throughout the growth cycle, whereas with treatment 3, plants several weeks old removed practically all of the potassium, nitrate, and phosphate before the end of three days. It was quite evident, therefore, that the actual cultural conditions were very different in these two cases, even though the same solution was used.

Not only was the yield of total dry matter altered, but also the composition of the plants as shown in table 1. The plants having at their disposal the larger volumes of solution contained a higher percentage of most of the elements of the culture solution.

The total concentration of the dilute solution was quite low, but similar considerations would apply to solutions of higher total concentration if the partial concentration of some rapidly absorbed ion were low, which condition would obtain in certain solutions of a series varying progressively in composition. The relative effects of different volumes of solution will depend upon the stage of growth of the plant and upon climatic conditions. A volume of solution which would be adequate for the growth of a plant in winter might become entirely inadequate in summer.

While it may be thought that these contentions require no argument, it is a fact that in many experiments which have been reported in recent years, insufficient attention has been paid to the rate of absorption of essential ions and to the total supply of these provided for each plant. Very recently, Trelease and Livingston (22) described an apparatus for growing plants in a continuously flowing solution, so that the roots may be bathed at all times in a solution of constant composition. Further comments on this procedure in relation to the soil solution will be made later.

TABLE 1

Composition and yield of barley plants grown in different volumes and concentrations of culture solutions

CULTURAL CONDITIONS PERIOD OF GROWTH—JUNE 6–JULY 23	STEMS AND LEAVES				ROOTS				STEMS AND LEAVES			ROOTS		
	Average air-dry weight of each plant	Composition			Average air-dry weight of each plant	Composition			Total amounts absorbed by each plant			Total amount absorbed by each plant		
		N	P	K		N	P	K	N	P	K	N	P	K
	gm.	*per cent*	*per cent*	*per cent*	*gm.*	*per cent*	*per cent*	*per cent*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*
1. 1 plant per 2 liters of solution of 1400 p.p.m. concentration. Total, 20 plants. Solution changed twice.	4.70	4.98	0.73	6.63	1.20	3.55	1.09	4.73	0.23	0.03	0.31	0.04	0.13	0.57
2. 1 plant per 2 liters of solution of 200 p.p.m. concentration. Total, 20 plants. Solution changed three times a week..	3.33	4.59	0.64	4.88	0.74	2.55	0.60	3.98	0.15	0.02	0.16	0.02	0.004	0.30
3. 6 plants per 1 liter of solution of 200 p.p.m. concentration. Total, 72 plants. Solution changed two times a week	0.91	2.98	0.92	3.50	0.32	1.96	0.49	2.10	0.03	0.008	0.03	0.006	0.002	0.07

One other suggestion may be advanced on the basis of the data given in table 1. The solution of low concentration evidently was not quite so favorable to growth as the regular culture solution, even when the total volumes of solution provided were sufficient to maintain a practically constant composition. In other words, the concentration of certain ions may become so low that the plant cannot absorb them at a rate sufficiently rapid to permit maximum growth. Here also the climatic conditions must be taken into consideration. It should be noted, however, that very good growth may be obtained even with a solution of a total concentration as low as 200 parts per million. The relation of the concentration of phosphate to plant growth is especially interesting and several experiments bearing on this point will be presented later in this article.

AVAILABILITY OF IRON AND PLANT GROWTH

In addition to variability and the absorption of ions by the plant, the question of an adequate supply of iron in solution cultures has been neglected in many investigations. Gile and Carrero (11) early called attention to the importance of maintaining a suitable concentration of iron in the culture solution, and the subsequent work of one of the writers emphasized this point. It is now generally recognized (21) that the assumption that colloidal iron phosphate would supply to the plant a sufficient quantity of this essential element is by no means justified for all types of solutions. Under many conditions it is necessary to use other forms of iron, such as iron citrate or tartrate.

COMPARISON OF THE GROWTH OF PLANTS IN SOLUTION CULTURES AND IN SOILS

We can readily admit that the relation of plant growth to the composition of the culture solution constitutes a problem which justifies itself without reference to the soil. On the other hand, the investigator in this field naturally possesses an interest in the growth of plants in solid media, the normal condition for most plants of agricultural interest. Moreover, many solution culture investigations are undertaken by agricultural experiment stations with the avowed purpose of elucidating the nature of soil and plant interrelations.

During the past ten years, various members of the staff of this laboratory have been engaged on a study of a group of soils kept under controlled conditions, with particular reference to the composition of the soil solution as affected by season or by crop growth. We have, therefore, had a rather unique opportunity for making certain comparisons between soil conditions and solution culture conditions.

In our first series of experiments along this line, we grew barley plants in solution cultures adjacent to tanks of different soils which were under investigation. Three different solutions in 4-liter bottles were used. Only one

plant was placed in each bottle and no changes of solution were made. Small amounts of iron tartrate were added about once each week. The bottles were buried up to their necks in soil in order to maintain an even temperature around the roots. In addition to these cultures, another set was arranged, using 1-liter bottles (1 plant to each bottle) and changing solutions each week throughout the season. At several periods, small aliquots were removed from the bottles of each of the three first sets and the composite samples so obtained were analyzed. Observations on height, number of tillers, and stage of development of the plants grown in the artificial culture solutions and in the soil were made at frequent intervals and compared. After harvesting, the plants were separated into grain, stems and leaves, and roots.

Tables 2 and 3 show that after nine weeks, only very small concentrations of nitrate remained, especially in solutions *B* and *C*, which had lower initial concentrations of this ion. Potassium and phosphate were greatly diminished in concentration, while the diminution in the concentration of calcium, magnesium and sulfate was far smaller. In solution *C*, which was one-third as concentrated as solution *A*, the nitrate was reduced to a low level by the sixth week of growth. All the solutions were distinctly acid at the beginning but by the time that the plants had grown for six weeks the reactions had all changed to pH 6.8. This reaction was maintained during the remainder of the season.

Table 4 shows that the highest yield was obtained from the cultures in which the solutions were changed throughout the season. The yield of plants grown in the solution of low concentration was much smaller than in the other cases. For purposes of comparison, there is included in the table data on plants grown in a fine sandy loam soil, producing at the rate of 64 bushels of grain per acre. As already stated, the soil and solution cultures were located adjacent to each other and the plants started to germinate at the same date.

It is apparent that solutions *A* and *B* produced much larger plants than those produced by a fertile soil. One reason for this may be inferred from a study of Tables 2 and 3. At the end of six weeks, there remained in the artificial culture solutions a considerably greater concentration of nitrate than in the soil solution. During the first five weeks, the growth of the plants in the soil cultures and in the solution cultures was almost parallel, but beginning with the sixth week the plants in the solution cultures began to put out many more tillers than the plants in the soil and at the end of the growth period, the former plants had several times as many tillers as the latter. In the case of the dilute solution *C*, the growth of the plants during the first few weeks was practically equal to that in the other solutions, but the supply of nitrate was exhausted early and, although the plants started to produce a great many tillers, the concentration of nitrate was not maintained long enough to permit of the normal development of these tillers.

TABLE 2

Effect of the growth of barley plants on the composition of different culture solutions

PERIOD	K*			Ca*			Mg*			NO_3*			PO_4*			SO_4*		
	Solution A	Solution B	Solution C	Solution A	Solution B	Solution C	Solution A	Solution B	Solution C	Solution A	Solution B	Solution C	Solution A	Solution B	Solution C	Solution A	Solution B	Solution C
	milli-equivalents			*milli-equivalents*			*milli-equivalents*			*milli-equivalents*			*milli-equivalents*			*milli-equivalents*		
Initial	4.1	4.9	1.3	8.7	4.2	2.9	4.0	6.0	1.4	11.1	8.6	3.7	1.2	1.2	0.4	4.5	6.3	1.5
After 6 weeks' growth	2.0	3.6	0.4	7.5	3.6	2.4	†	†	†	5.7	4.0	0.6	0.8	0.9	0.2	3.9	5.8	1.1
After 9 weeks' growth	0.4	1.4	0.1	5.9	2.9	1.9	3.1	4.7	1.1	2.6	0.2	0.1	0.2	0.3	0.03	3.0	4.8	0.9
At time of harvest, 17 weeks	0.4	0.9	0.2	2.6	1.6	0.9	1.0	2.1	0.2	0.0	0.0	0.0	0.2	0.2	0.04	‡	‡	‡

* In addition to the elements listed above, there was added to these solutions approximately 0.5 p.p.m. Mn as the sulfate. Iron was added at intervals in the form of ferric tartrate. The solutions also contained small amounts of sodium chloride, from 5 to 25 p.p.m.

† Determinations lost.

‡ Some evidence of bacterial decomposition, determinations not made.

TABLE 3

*Change of concentration of NO_3 in soil solution during growth of barley crop**

PERIOD	CONCENTRATION OF NO_3
	milli-equivalents
At planting date	3.7
After 2 weeks	7.4
After 4 weeks	6.1
After 6 weeks	1.6
After 8 weeks	0
After 10 weeks	0
After 12 weeks	0
After 14 weeks	0

* These data were obtained on a tank of fine sandy loam soil (No. 11), located adjacent to the solution culture experiments.

TABLE 4

Description of barley plants grown in solution and soil cultures

CULTURES	TOTAL NUMBER OF PLANTS	AVERAGE HEIGHT OF PLANTS	AVERAGE NUMBER OF HEADS PER PLANT	AVERAGE WEIGHT OF HEADS PER PLANT§	AVERAGE NUMBER OF TILLERS	AVERAGE WEIGHT OF STRAW PER PLANT§	AVERAGE WEIGHT OF GRAIN PER PLANT§	AVERAGE WEIGHT OF KERNELS§	TOTAL DRY MATTER IN GRAIN
		cm.		*gm.*		*gm.*	*gm.*	*gm.*	*per cent*
Solution A	19	100±1.8‡	21±0.62	24±1.5	25±0.77	36±1.7	22	0.043	37
Solution B	20	106±1.6	15±0.48	20±1.1	17±0.51	28±0.80	16	0.047	33
Solution C	16	73±1.6	10±0.29	7±0.42	14±0.41	14±0.31	5	0.038	24
Solution A (frequent changes)	15	95±2.6	32±0.99	55±1.6	41±1.3	54	48	0.041	44
Soil*	35†	104±1.5	7±0.36	12±0.70	8±0.34	10±0.47	10	0.049	45

* The crop grown on this soil (No. 11), yielded at the rate of 64 bushels of grain per acre.
† Area of soil allowed for growth of each plant 36 sq. in.
‡ Probable error of the mean.
§ On air-dry basis.

Details of experiment

Solutions, A, B and C remained unchanged during the entire season, but 4-liter bottles were used and only one plant was placed in each bottle. These bottles were buried in the ground up to their necks.

For solution A (changed frequently), 1-liter bottles with one plant in each bottle were used. In this case, the solutions were changed at approximately weekly intervals throughout the season.

Period of growth, May 13 to October 1.

Solution *A* had an entirely different composition from solution *B*. In solution *A* the equivalent weight of calcium was more than twice that of magnesium, while in solution *B* more magnesium was present than calcium. Solution *A*, it is true, produced a slightly greater yield of dry matter than

solution *B*, but if this difference is significant it can be attributed to the difference in the concentration of nitrate in the two solutions. There is no reason to believe that the different ratios between the various ions had any effect on growth. In the experiments of Davis already mentioned, it was found that solutions of widely different composition produced equal weights of wheat plants within the experimental error.

The plants grown in the changed solutions were of exceptional size. They continued to put out new tillers for a much longer period than the other plants. The increased growth was not merely vegetative, however, since the total grain produced by each plant was also much greater. In fact the proportion of grain to total dry matter exceeded that for the other plants. The ripening processes were, however, much delayed.

Some striking differences in composition are recorded in table 4. The plants grown in the frequently changed solution had an entirely different composition from that of the plants grown in a similar solution unchanged. In the changed solution the percentage of nitrogen and potassium in the straw was much higher. In the grain, the percentages of calcium, magnesium and potassium were all very much the same but the nitrogen content of the grain from the plants grown in the frequently changed solution was much higher than that from the plants grown in the unchanged solution. The percentage of phosphorus was also significantly increased. The difference in the composition of solutions *A* and *B* was reflected in the composition of the straw and of the roots. This difference was especially noticeable for the percentage of calcium in the straw. There was an entirely different ratio of calcium to magnesium in the two cases, but as we have indicated already, this fact probably has no significance in so far as the total yield of crop is concerned.

COMPARISONS OF THE GROWTH OF PLANTS IN SAND AND SOLUTION CULTURES

A very important consideration should be kept in mind in planning experiments with sand cultures. If these are to be compared with solution cultures, the same volume of solution should be provided for each plant in both cases. This obviously means that much larger containers must be provided for the sand cultures than for the solution cultures. For example, if one liter of solution is provided for a given number of plants in a solution culture, then there would be required for a comparable sand culture (at 12.5 per cent moisture content) eight kilograms of moist sand. Unfortunately in almost all of the sand culture experiments heretofore reported, this precaution has been neglected and the amounts of sand used have been so small that the total amounts of culture solution available to the plants have been very restricted. Under these circumstances, it may well have happened that the growth of the plants was limited by an inadequate supply of one or more essential elements. There is considerable inconvenience attendant upon the use of large jars and large quantities of sand, but it is essential, nevertheless, to

give heed to the volumes of culture solution provided. Disregard of this matter may also lead to erroneous ideas concerning the effect of different hydrogen-ion concentrations on plant growth, since the initial reaction of the solution may be changed with extreme rapidity.

Barley was grown in both sand and solution cultures. One liter of solution was provided for each plant and six changes of solution were made during the experiment. The plants were twelve weeks old when harvested. The method of McCall (17) was used in making the changes on the sand cultures. The seeds were planted in the sand cultures at the same time that the seeds for the solution cultures were placed in the germinating pan, both at the same temperature. If seeds already germinated are afterward transplanted to sand, the roots are likely to be injured and a temporary inhibition of growth may take place.

TABLE 5

Composition of barley plants (at maturity) grown in different solutions

CULTURES	K			Ca			Mg			N			P		
	Straw	Grain	Roots	Straw	Grain	Roots	Straw	Grain	Roots	Straw	Grain	Roots	Straw	Grain	Roots
	per cent			*per cent*			*per cent*			*per cent*			*per cent*		
Solution A....	1.19	0.50	0.57	1.05	0.10	0.56	0.29	0.15	0.12	0.41	1.29	0.69	0.14	0.39	0.26
Solution B....	1.78	0.50	1.05	0.58	0.06	0.33	0.32	0.16	0.20	0.36	1.26	0.65	0.15	0.45	0.24
Solution C....	0.75	0.48	0.95	0.96	0.07	0.32	0.26	0.17	0.15	0.45	1.36	0.49	0.15	0.50	0.21
Solution A*....	2.72	0.52	0.59	1.17	0.08	8.40	0.33	0.16	0.34	0.92	2.14	1.39	0.15	0.54	2.63
Soil†.....	1.80	0.51		0.54	0.05		0.21	0.13		0.34	1.41		0.08	0.44	

* Changed frequently.

† Fine sandy loam soil yielding at rate of 104 bushels of grain per acre. (Not the same soil as that referred to in table 3). Area of soil allowed for growth of each plant 18 sq. in.

Although the number of plants employed in this experiment were too few in number, the differences in the composition of the plants grown under the two different conditions are significant (table 6). Except for phosphorus in the stems and leaves, larger percentages of all the elements were found in the plants grown in the solution cultures. A larger dry weight of plants was obtained, however, from the sand cultures.

In another experiment (table 7), the plants were grown to maturity. Each plant was provided with 1500 cc. of solution and no changes of solution were made. Here again the percentages of inorganic elements were higher in the plants grown in the solution cultures. Also, the yield from the sand cultures was greater than that from the solution cultures, especially the yield of grain. The percentage of grain and the average weight of kernels were greater in the case of the sand cultures.

In these and in other experiments we have noted that tillering proceeds more rapidly in sand cultures than in solution cultures. This fact may, perhaps, be explained on the basis of the more profuse development of root sys-

TABLE 6

Composition of plants grown in sand and solution cultures

CULTURE	AVERAGE AIR-DRY WEIGHT OF EACH PLANT	STEMS AND LEAVES					ROOTS				
		K	Mg	Ca	N	P	K	Mg	Ca	N	P
	gm.	per cent					per cent				
Sand—12 plants	26.3	2.43	0.35	0.90	2.25	0.64	0.97	0.26	1.04	1.36	0.35
Solution—12 plants	13.8	3.25	0.49	1.48	2.98	0.61	1.60	0.34	2.62	2.66	1.32

Details of experiment

The plants were grown from July 23 to October 20.

One liter of solution was used for each plant. 6 changes of solution for both solution and sand cultures. The same total quantities of solution were provided for each plant in both solution and sand cultures.

TABLE 7

*Comparison of yields and of composition of barley plants grown in sand and solution cultures to maturity**

	AVERAGE WEIGHT (WATER-FREE BASIS) OF EACH PLANT	COMPOSITION				
		K	Ca	Mg	N	P
	gm.	per cent	per cent	per cent	per cent	per cent
Sand culture:						
Stems and leaves	6.63	1.52	0.89	0.32	0.44	0.09
Chaff	1.50	1.31	0.61	0.35	0.50	0.13
Grain	9.92†	0.47	0.06	0.12	1.54	0.38
Entire plant (roots excluded)	18.05					
Solution culture:						
Stems and leaves	6.17	2.21	1.40	0.43	0.77	0.24
Chaff	1.67	1.70	0.82	0.31	1.00	0.32
Grain	6.00‡	0.63	0.06	0.14	1.89	0.51
Entire plant (roots excluded)	13.54					

Description of plant (grown from May to September)

CULTURE	NUMBER OF PLANTS GROWN	ANERAGE HEIGHT	AVERAGE NUMBER OF HEADS PER PLANT	AVERAGE AIR-DRY WEIGHT OF HEADS PER PLANT	AVERAGE NUMBER OF TILLERS PER PLANT	AVERAGE AIR-DRY WEIGHT OF STRAW PER PLANT	AVERAGE AIR-DRY WEIGHT OF KERNELS
		cm.		gm.		gm.	gm.
Sand	24	74.7±0.82§	12.0±0.55	12.3±0.42	12.7±0.57	7.13±0.26	0.050
Solution	24	74.8±0.92	11.5±0.38	8.1±0.31	12.0±0.33	6.50±0.33	0.039

* Total volume of culture solution supplied to each plant was 1500 cc., the same in both solution and sand cultures.

† 55 per cent of entire plant.

‡ 43 per cent of entire plant.

§ Probable error of the mean.

tems in sand cultures. Gericke (10) has suggested that tillering is related to root development. If it is a fact that a sand culture offers a more favorable medium for plant growth than a solution culture, the explanation cannot be based on the total intake of essential elements, since plants developed under solution culture conditions may have the higher percentage of these elements. There are other differences in the conditions of sand and solution cultures. Very appreciable amounts of silica derived from the sand enter into solution and plants grown in sand may contain considerable quantities of silica in the stems and leaves. The conditions of aeration are, of course, different in these two types of cultures, and this is sometimes considered the principal difference.

THE SOIL SOLUTION IN ITS PHYSIOLOGICAL ASPECT

The ideas which are now held concerning the soil solution as a medium for supplying essential elements to plants have been reviewed by Burd and Martin (5).

The original investigations of this laboratory on the soil solution began with a study of water extracts of various soils kept in tanks under conditions as carefully controlled as possible. It was found in general that these water extracts were subject to great changes in composition and concentration during the course of the year. The growth of barley and of other plants had a pronounced influence in diminishing the quantity of material which could be extracted with water. The most notable change was in nitrate, which was generally reduced to a negligible concentration by the time the plants had made their maximum growth. Definite decreases in the amounts of water extractable calcium and magnesium also occurred at this time. The decreases in potassium were less marked in character but they seemed to be significant in the majority of soils examined. No clear evidence was obtained of consistent changes in water extractable phosphate during a single season.

At the time that the investigations were begun, the methods of water extraction seemed to be best adapted to achieve the purposes in view. It was realized, however, that an extract made with five parts of water to one of soil, was not identical with the soil solution. Shortly afterward, Bouyoucos and McCool (2) described a cryoscopic method for determining the concentration of the soil solution at any desired moisture content. This method (12) was applied to the same soils which were being studied by means of water extracts. There was found to be a good general agreement between these two methods as far as general changes in total concentration were concerned. Both procedures indicated that the concentration of solutes in the soil moisture varied at different times during the season and that there was a significant decrease in concentration brought about by the growth of crops.

Measurements of the freezing point depressions of the soil solution *in situ* were supplemented by observations on extracts of several soils (15) made with very small proportions of water, after these extracts had been concentrated so as to have the same depressions as those of the corresponding soils at approximately the optimum moisture content. It was found that these concentrated extracts could be passed through another portion of the moist soil without essential change, and it was thought that this evidence justified the conclusion that a solution possessing such properties did not differ greatly from the actual soil solution, as it existed in the soil under those particular conditions.

The results of these various lines of inquiry led to the assumption that water extracts, while not themselves identical with the soil solution, did reflect changes in this solution in a consistent manner. At this stage of the investigations the only direct evidence concerning the total concentration of the soil solution was that based on freezing point depressions. An attempt was made to use these data for the purpose of computing the quantity of material dissolved from the soil by a 1–5 extract, in addition to such material contained originally in the soil solution. Before performing such computations, it was essential to decide whether

or not all of the soil moisture was effective as a solvent. If it were assumed that all of the soil moisture acted as a solvent, then the amount of additional material dissolved by the 1–5 extract could not be considered very great in most cases. But Bouyoucos found that when the freezing point depressions of soils were determined at different moisture contents, there was an abnormally great increase in the values obtained under low moisture conditions. This observation led to the theory that a considerable proportion of the total moisture of a soil might be held in "unfree" form and not act as a solvent. The amount of unfree water would vary greatly with different soils. On this basis, the total amount of dissolved material contained in a given mass of soil would be less than if all of the water functioned as a solvent. On the basis of the unfree water hypothesis, it was estimated that the 1–5 water extracts dissolved from the soils used in our investigations a considerable quantity of material not originally present in the soil solution.

Later Keen (16) made a mathematical analysis of some of the freezing point data published by Bouyoucos and showed that there was no sharp line of demarcation between the different forms of water in the soil and also suggested that the proportion of unfree water was not constant, but varied with the total moisture content. These conclusions are not accepted by Bouyoucos (1), who states that dilatometer measurements indicated that the unfree water was sensibly constant regardless of the total water content of the soil.

About this time Parker (19) published a description of a modern application of what may be regarded as one of the oldest methods for studying the soil solution, the displacement method. As an incident to this investigation, Parker reached the conclusion that depressions of the freezing point may not measure the true concentration of soil solutions, since the finely divided or colloidal material of the soil exerts a pronounced effect on the freezing point depression, regardless of the solutes contained in the soil solution. Parker further concluded that all or nearly all of the water in soils functions as a solvent.

The question of whether finely divided material in itself produces a lowering of the freezing point as suggested by Parker, is an interesting one and the writers have made some measurements on aluminum oxide (Baker's analyzed, 200-mesh fine) at different moisture contents. When the oxide was washed free from soluble impurities, it was found that there was no appreciable depression of the freezing point, even at the lowest moisture contents at which a determination could be made. Sugar solutions added to the dry aluminum oxide had practically the same freezing point depression as in the free state.

While it is therefore not proved that merely finely divided material affects the freezing point depression, yet it is a fact that the solution displaced from a soil at a low moisture content may be much less concentrated than would be inferred from the freezing point depression made on the soil at the same moisture content. But so far it does not appear that freezing point depressions made on soils (at least on those used in our experiments) at optimum moisture content are affected to more than a slight extent by these new considerations. We have frequently found that soils at the time of the most active absorption of solutes by a barley crop showed extremely small depressions of the freezing point, yet the influence of the finely divided or colloidal material must have been exerted at all times during the season. Also, Burd and Martin (5) have found only comparatively slight differences between the freezing point depressions of soils and those of the displaced solutions, when moisture contents were not below the optimum.

Recently Burd and Martin (5) made an extensive and critical study of the Parker displacement method and introduced several modifications in the technique. The results of their experiments have a very significant bearing on the questions now under discussion. The simplest interpretation of the data would exclude the idea that any important amount of water in the soil does not act as a solvent. If this conclusion be correct, then it is unnecessary to take into account unfree water in comparing the amounts of material present in a water extract and in the soil solution. In other words, the water extract is made up more largely of solutes derived from the soil solution than was at first assumed. Nevertheless, Burd and Martin have shown that 1–5 extracts of the soils examined by them contained

larger amounts of certain solutes, particularly of potassium and phosphate, than were found in the soil solution. All considerations lead to the same conclusion with regard to phosphate, namely, that this ion is likely to exist in the soil solution only in very low concentration, and that the excess of phosphate dissolved in a water extract is very great.

Some of these conclusions were confirmed by still another method. Burgess (7) working in this laboratory, applied the Lipman pressure method to the study of a group of fine sandy loam soils and from his studies reached the conclusion that unfree water did not exist to any appreciable degree in these soils.

It is beside the purpose of the present discussion to consider the forms of water in a soil, but it may be remarked in passing that it seems possible that water may sometimes be combined or adsorbed and yet act as a solvent. Browne (4) suggests that a similar condition exists in ferric oxide hydrosols. We must acknowledge, however, that these questions cannot be regarded as settled at the present time.

CONCENTRATION OF PHOSPHATE IN SOIL SOLUTIONS AND IN CULTURE SOLUTIONS

One of the most striking differences between a soil solution and an artificial culture solution is found in the concentration of phosphate. Even a fertile soil may contain only a very low concentration of phosphate in its solution. Burd and Martin demonstrated this point by means of the displacement method. The series of fine sandy loam soils examined by them contained 3 to 12 parts per million of the phosphate ion in the solutions obtained from the uncropped soils. In ordinary culture solutions, the initial concentration of phosphate is far higher than this. For example, in one of Shive's solutions, approximately 1400 parts per million of this ion are present. Can plants be grown in culture solutions with concentrations of phosphate similar to those found in soil solutions? Comber (8) has suggested that plants may absorb phosphate from soils in a different way than they do from artificial culture solutions.

The authors, accordingly, carried out experiments (tables 8, 9, and 10) during two seasons for the purpose of studying the growth of plants in culture solutions with very low concentrations of phosphate. These experiments were attended with some difficulty since it was necessary to maintain the concentrations of phosphate fairly constant. The procedure adopted was to use large volumes of solution and to add at frequent intervals new portions of phosphate, in the form of KH_2PO_4. After the plants had grown for several weeks it was necessary to make these additions every day. In order to control the concentrations, small samples of solution were removed from each bottle several times each week, and these samples composited for analysis. Very good growth of barley plants occurred in solutions with concentrations of phosphate as low as those of the soil solution. In the first season's experiment, the supply of essential elements other than phosphate was very abundant and the yield obtained from the solution with an average of 9 parts per million of phosphate was greater than those from the solutions containing 0.7 or 2.4 parts per million. But even with the lowest concentration of phos-

phate, the average dry weight of each plant was greater than that of plants grown at the same season in soils producing at the rate of 25 to 65 bushels of grain per acre. In the second experiment, the concentration of the culture solution was reduced to one-third of that employed during the first season, and the solution of 10.8 parts per million of phosphate did not produce any greater yield than that containing 3 parts per million of phosphate. The

TABLE 8

Comparison of yields and composition of barley plants grown in solutions of different concentrations of PO_4

	AVERAGE WEIGHT (WATER-FREE BASIS) OF EACH PLANT	COMPOSITION				
		K	Ca	Mg	N	P
	gm.	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Solution of 0.7 p.p.m. PO_4:						
Stems and leaves	6.13	3.48	1.77	0.34	1.85	0.32
Chaff	1.70	2.00	1.04	0.34	1.84	0.52
Grain	4.60	0.77	0.08	0.16	2.58	0.59
Entire plant (roots excluded)	12.43					
Solution of 2.4 p.p.m. PO_4:						
Stems and leaves	9.50	3.44	1.74	0.42	1.69	0.27
Chaff	2.80	1.76	0.91	0.36	1.66	0.42
Grain	5.40	0.59	0.10	0.16	2.84	0.63
Entire plant (roots excluded)	17.70					
Solution of 9.0 p.p.m. PO_4:						
Stems and leaves	10.80	2.90	1.48	0.48	1.05	0.23
Chaff	2.97	1.99	0.86	0.36	1.17	0.33
Grain	9.60	0.74	0.08	0.15	2.32	0.58
Entire plant (roots excluded)	23.37					
Regular culture solution, 120 p.p.m. PO_4:						
Stems and leaves	6.17	2.21	1.40	0.43	0.77	0.24
Chaff	1.67	1.70	0.82	0.31	1.00	0.32
Grain	6.00	0.63	0.06	0.14	1.89	0.51
Entire plant (roots excluded)	13.84					

solution containing 1.1 parts per million yielded almost as much in total dry matter as either of the others. All the solution cultures produced larger plants than those produced by a soil yielding at the rate of 40 bushels of grain per acre. In the soil cultures, the plants were spaced more widely than in ordinary field practice. Further reference to this latter point will be made presently.

TABLE 9

Description of barley plants grown in solutions of different phosphate concentration
(Air-dry basis)

DESCRIPTION OF SOLUTION	TOTAL NUMBER OF PLANTS	AVERAGE HEIGHT	AVERAGE NUMBER OF HEADS PER PLANT	AVERAGE WEIGHT OF HEADS PER PLANT	AVERAGE NUMBER OF TILLERS PER PLANT	AVERAGE WEIGHT OF STRAW PER PLANT	AVERAGE WEIGHT OF AIR-DRY GRAIN PER PLANT	AVERAGE WEIGHT OF KERNELS	PROPORTION OF GRAIN IN TOTAL DRY MATTER
		cm.		*gm.*		*gm.*	*gm.*	*gm.*	*per cent*
0.7 p.p.m. PO_4	30	70.3±0.59*	13.9±0.53	6.95±0.40	16.2±0.61	6.76±0.31	4.60	0.033	40
2.4 p.p.m. PO_4	30	77.0±0.88	19.7±0.75	9.28±0.30	21.4±0.75	10.95±0.35	5.40	0.033	33
9.0 p.p.m. PO_4	30	78.5±0.87	21.3±0.84	14.22±0.64	22.4±0.85	12.68±0.51	9.60	0.034	43
Regular solution, 120 p.p.m. PO_4	24	74.8±0.92	11.5±0.38	8.08±0.31	12.0±0.33	6.50±0.33	6.00	0.039	48

* Probable error of the mean.

Details of experiment

The concentration of phosphate in the first three solutions was maintained approximately as indicated above by the daily addition of small amounts of KH_2PO_4. Samples of the solutions were taken every few days and analyzed for PO_4. Four-liter bottles were used with 2 plants in each bottle. The solution was changed once after 39 days of growth. Plants in regular culture solution were grown in 2-liter bottles with 2 plants in each bottle and here the solution was not changed.

The average weight of grain for individual plants from adjacent soil cultures was 3.0 gm. This is an average of 13 soils yielding at the rate of 25 to 65 bushels per acre.

The average weight of the total dry matter per plants was 6.0 gm.

The number of plants grown in the tanks of soil allowed a space of 17 sq. in. for each plant.

TABLE 10

Description of barley plants grown in solution of different phosphate concentrations

DESCRIPTION OF SOLUTION	TOTAL NUMBER OF PLANTS	AVERAGE HEIGHT	AVERAGE NUMBER OF HEADS PER PLANT	AVERAGE WEIGHT OF HEADS PER PLANT	AVERAGE NUMBER OF TILLERS PER PLANT	AVERAGE WEIGHT OF STRAW PER PLANT	AVERAGE WEIGHT OF GRAIN PER PLANT	AVERAGE WEIGHT OF KERNELS	PROPORTION OF GRAIN IN TOTAL DRY MATTER
		cm.		*gm.*		*gm.*	*gm.*	*gm.*	*per cent*
1.1 p.p.m. PO_4 ..	30	79±0.76*	5.0±0.13	5.6±0.21	5.4±0.04	3.4±0.04	4.6	0.036	50
3.0 p.p.m. PO_4...	30	80±1.0	4.8±0.16	5.1±0.23	5.4±0.15	4.6±0.17	4.2	0.034	43
10.8 p.p.m. PO_4..	30	83±0.82	4.3±0.04	5.0±0.21	5.0±0.17	4.8±0.16	4.2	0.039	43

* Probable error of the mean.

Details of experiment

Four liters of solution in each bottle supported two plants. The solution had one-third the concentration of that used in preceding experiment and was not changed.

The average amount of grain produced by a plant on adjacent soil was 3 gm. This soil yielded 40 bushels per acre.

Average total dry matter per plant was 6.3 gm.

GENERAL COMPARISONS BETWEEN PLANTS GROWN IN SAND, SOIL AND SOLUTION CULTURES

While in recent years, many experiments have been reported in which the technique of solution or of sand cultures has been used, ordinarily no detailed description of the plants is given. Some of the photographs published show plants that seem to be more or less stunted even though grown in what were considered the best solutions. That is to say, even though the composition of the culture solutions was entirely favorable, some other condition may have limited growth. At certain seasons climatic factors may have been responsible but in other cases it is extremely probable that the total volume of solution supplied to each plant was inadequate.

What constitutes a normal plant and upon what basis should comparisons be made between plants grown under different conditions? Under a favorable climatic environment, it is possible to produce from a single barley seed a plant with as many as forty tillers and thirty or more heads. Individual plants from fertile soils under ordinary conditions of planting are much smaller than this. The size of the individual plants produced in a soil depend in part upon the number of plants grown in a given area or volume of soil. Within rather wide limits, the total yield from a given mass of soil may be relatively constant regardless of the number of plants [Brenchley (3) and Burd in some unpublished data]. In much the same way, the size of the plant produced in solution or sand cultures will vary with the volume of solution, the number

of plants grown in each container, and the number of times the solution is changed. For this reason (cf. table 1), it is possible to obtain plants of entirely different size, the total growth depending upon the capacity of the container and the frequency with which the solution is changed. If the climatic conditions are not sufficiently favorable, a small amount of culture solution may be capable of producing plants as large as can be grown under that particular aerial environment. This will also be true if plants are grown only for short periods.

From this discussion it is apparent that normality as applied to plant growth is a relative term. We are not justified in saying that a normal plant is one making the best growth under a given set of environmental conditions since it is evident that certain environments would affect the plant adversely. Thus a certain plant would be the best that could be grown under certain particular conditions yet would be abnormal when compared to plants grown under more favorable environments. Normal plants may vary in total growth and may be produced under a relatively wide range of conditions. With these facts in mind it is evident that no exact standard for a normal plant can be established. It might be permissible to accept as a standard for comparison a plant of the same species grown in a productive soil and under similar climatic conditions.

If it is desired to make any exact comparisons of different solutions with reference to the growth of plants over extended periods, it is necessary either to use large volumes of solution for each plant or else to use a continuously flowing solution, as suggested by Trelease and Livingston (22). By this means, the composition of the culture solution may be maintained constant and very interesting information obtained in connection with certain problems, but the comparison of many different solutions in this way would involve great technical difficulties.

In view of some unpublished findings by Davis and in consideration of what has already been said here, it is fair to question the profit in comparing solutions of slightly varying composition. At least, more should be required than the control of the culture solutions. The adequacy or the toxicity of any given solution or cultural arrangement is very much dependent upon climatic conditions. This fact is strikingly illustrated by the recent experiments of Davis in which it was found that two solutions of extremely different composition produced equally good yields of wheat during certain months of the year and during other months produced significantly different yields. Not the least important factor of the climatic complex is light. One of the writers has found that even comparatively slight shading during the summer months decreased the growth of barley plants to a marked degree and altered their composition with regard to inorganic elements even though the temperature was maintained at essentially the same point around the shaded and the fully illuminated plants.

Our present knowledge enables us to state with considerable assurance that we cannot hope to demonstrate a "best" solution for any plant. It cannot be expected that any two investigators will agree in their findings unless all conditions, light, temperature, humidity, volumes of culture solution, variability, etc., are controlled. The relations of a plant to its culture medium are dynamic and no solution has any fixed value for plant growth. These remarks are made in a constructive spirit and are not directed in opposition to those who have initiated such researches in the field of plant nutrition.

There is still another phase of experimentation with plants in artificial cultures which has perhaps received insufficient attention. Most culture solutions are made up with only six elements, aside from iron. It is probable that other elements may be essential, at least in small amounts. McHargue (18) has demonstrated this to be so in the case of manganese. In our experiments with barley, we have not found manganese necessary, but this may only mean that sufficient manganese was present as an impurity in the salts used. In determining the essential nature of elements required, probably in traces only, it becomes necessary to employ highly purified salts. Even then, an ample supply may be furnished by the seed.

EXPRESSING THE COMPOSITION OF CULTURE SOLUTIONS

The triangular diagram system is ingeniously adapted to the presentation of the data on yields obtained from many different solutions, but in view of the difficulties met with in the interpretation of such data, it is possible that the diagrams sometimes may become misleading. It may also be suggested that it is desirable to place the emphasis on the ions of the solution rather than on the salts used in preparing them. It is admitted that in a complex culture solution, the chemist is not prepared to speak with any certainty concerning the concentrations or activities of individual ions. Nevertheless, the culture solutions are ordinarily very dilute and the degree of dissociation high. Also, as plants absorb ions from the solutions undissociated molecules dissociate to restore the equilibrium. There is much evidence from absorption studies that plants absorb the elements of the culture solution in ionic form (14).

In earlier work, we have been accustomed to express the composition of culture solutions in terms of parts per million. Undoubtedly this method served the purposes in view at that time but with the carrying out of more intensive studies it has become necessary to interpret the data in terms of chemical equivalents. It seems to the authors that the most satisfactory method of describing culture solutions in all experiments of the type now under consideration, is in terms of milliequivalents. (In water analysis, these are called reaction values.) Total concentrations may be expressed in terms of parts per million or as osmotic pressures even though osmotic pressure may not have any particular physiological significance in dilute culture solutions.

INTERPRETATION IN RELATION TO SOIL PROBLEMS

It may be well to consider further some of the similarities and dissimilarities between growth conditions in soil and solution cultures. One of the methods frequently employed with solution cultures is to change solutions every three days throughout the growth cycle of the plant. The plant is, therefore, subjected to alternating conditions in the culture medium. Conditions in the soil are likely to be quite different from this. The soil solution gradually decreases in concentration during the growth of the plant and during the latter stages very little nitrate remains in the soil solution. There may also occur a decrease in the concentration of calcium, magnesium, and potassium. Phosphate may possibly increase in concentration, because of the withdrawal of certain cations from the solution, as suggested by Burd and Martin (6). Later studies (unpublished data), indicate that during the growth of barley plants in soils which are not subject to leaching and in which the calcium concentration is only slightly decreased, the phosphate concentration is significantly lowered. A continuously flowing solution also fails to provide a medium like that of the soil, although this is no argument against the use of such technique for special purposes.

Probably the conditions in the experiment described on page 379 imitated soil solution conditions to a considerable extent. In this experiment, the solution was not changed and the concentration of ions was decreased by absorption by the plant. It is probable, however, that potassium was reduced to a lower concentration than in most soil solutions.

Aside from phosphate, the authors have found no fundamental dissimilarity in composition or concentration between culture solutions such as those described in table 2 and soil solutions displaced from soils early in the season. It does not seem to be necessary to assume that plants absorb essential elements from soils by some special mechanism entirely different from that operative in solution cultures.

While the composition of the solution displaced from a soil may represent, on the average, the solution from which plants absorb their mineral elements, there are undoubtedly certain complications introduced by the presence of the solid medium. The composition of the soil solution in immediate contact with absorbing roots may not be the same as that displaced from the mass of the soil as a whole. Diffusion of ions in soils is far slower than in solution cultures, and the absorption of ions from the soil solution seems to depend to a great extent upon the ability of the plant to extend its root system (20). It would seem that the nitrate ion diffuses readily through the soil solution since all, or practically all of the nitrate is removed from a soil contained in a tank even though the absorbing roots do not come into contact with every portion of the solution. Different ions diffuse at different rates and this fact would also have to be considered in drawing deductions regarding what may be called the "physiological selection." It is also probable that as root growth

and the absorption of ions proceed, not all of the root system would be bathed at any one time in exactly the same soil solution. In solution cultures, diffusion must be extremely rapid. Sand cultures would partake of the nature of the soil to a limited extent. The differences in the rates of diffusion of ions in sand cultures and in solution cultures is reflected in the composition of the plants grown in sand and solution cultures, as we have already pointed out. On the other hand, in both sand and soil cultures, the proportion of roots to tops is much greater than in solution cultures. The comparisons which have just been made refer particularly to soils kept at the optimum moisture content. Burd and Martin (5) have shown that as the moisture content of a soil decreases, the concentration of some of the ions of the soil solution increases almost proportionately, so that the effect of variations in the moisture content of the soil, often occurring during the season, must be taken into consideration. While the concentration of the soil solution is increased at low moisture contents, the physiological availability of ions and of water may be decreased and it is impossible at present to determine the nature of the physiological relations existing between the plant and the soil solution at low moisture contents.

Notwithstanding that solution culture conditions are in certain respects abnormal for most agricultural plants, plants like barley can be carried through their complete cycle of growth and very large and well developed plants can be produced. There is one difficulty which is often encountered at the final stage of growth under solution culture conditions. Roots may undergo bacterial decomposition at this time so that the final ripening of the grain is interfered with. In several experiments, however, we have found the average weight of the kernels produced in solution culture about 80 per cent of than the weight of those produced in a good soil. We have also compared the relative germinating powers of seeds grown under these different conditions and have found no differences.

GENERAL DISCUSSION

This survey of experiments leads to several general conclusions. As might naturally be expected, plants have great powers of adaptation to different cultural conditions. It is not at all necessary that some specific solution be provided. The essential condition of good growth, as far as the mineral elements are concerned, is that the concentration of each element be maintained above its critical level. The culture solution must be replenished as absorption of ions by the plant proceeds in order to maintain the concentration of any essential element above its critical concentration. Finally the conditions of light and temperature are of paramount importance in determining the adequacy of concentration of any essential element.

Although it has been the purpose of this article to point out some of the many difficulties to be overcome in interpreting, in terms of soil problems,

data obtained from experiments with artificial culture solutions, it is not intended to depreciate the value of such experiments. Indeed, the use of solution culture technique seems to offer the most promising means of solving some of the most important questions of plant nutrition. It may be suggested, however, that the time has arrived for the intensive study of plant growth from the standpoint of chemical metabolism. It is highly essential to learn more about the functions of different elements in the chemical system of the plant. This knowledge must be available before any satisfactory understanding of the relation of culture solutions to plant growth can be attained.

SUMMARY

A brief review is given of various precautions to be taken in interpreting the results of experiments with artificial culture solutions. Additional evidence is presented concerning the importance of taking into consideration the absorption of ions by the plant in planning such experiments.

Barley plants grown in solution, sand, and soil under identical climatic conditions, are compared with reference to total dry weight, number of tillers, grain production, etc.

A brief résumé of the present theories on physiological aspects of the soil solution is given.

Experiments are reported in which barley plants were grown in culture solutions containing phosphate in very low concentrations, maintained approximately constant. Good growth was obtained under these conditions and analogies to the soil solution are pointed out.

Attention is called to certain dissimilarities between soil solutions and artificial culture solutions, as the latter are ordinarily employed. It is concluded, however, that there is no evidence from comparative experiments that plants absorb mineral elements from the soil by a mechanism different from that operative in solution cultures.

The need for conducting more intensive chemical studies of plant growth is pointed out.

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